**IMPLEMENTATION AND VALIDATION OF FAULT-RUPTURE
RESPONSE SPECTRUM ANALYSIS PROCEDURE IN
CSIBRIDGE™ FOR BRIDGES CROSSING EARTHQUAKE FAULT
RUPTURES**

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Title Implementation and Validation of Fault-Rupture Response Spectrum Analysis Procedure in CSiBridge™ for Bridges Crossing Earthquake Fault Ruptures

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ABSTRACT

Validation and Implementation of a Simplified Analysis Procedure for Bridges Crossing Earthquake Fault Ruptures

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This thesis evaluates the application of a simplified analysis procedure as implemented in version 16 of CSiBridgeTM for design of bridges crossing earthquake fault ruptures. The fault-rupture response spectrum analysis (FR-RSA) approximation method has been proved adequate for both straight and curved ordinary bridges, but lacked a comfortable interface to accommodate the method users. Computers and Structure, Inc. has implemented the FR-RSA procedure into CSiBridgeTM, a user-friendly integrated 3-D bridge design software, as an added seismic design feature. By combining the response of the bridge due to the quasi-static displacement from the fault strike-slip rupture and the pseudo-dynamic displacement from the earthquake response spectrum analysis, a combined seismic demand is approximated using the software. The CSiBridgeTM bridge model creation process and application of FR-RSA as the Caltrans Fault Crossing Seismic Design Request is explained and evaluated in this thesis. In order to validate the implementation of FR-RSA in CSiBridgeTM v.16, the bridge demands for a three span and a four span curved bridge crossing earthquake fault rupture zones from the analytical models developed in Open System for Earthquake Engineering Simulation (OpenSees) and CSiBridgeTM v.16 are compared and discussed. It was found that the displacement demands from the abutments and bents were comparable from the two programs, supporting the correct application of the approximation method. This thesis also presents recommendations for improving the analysis function of CSiBridgeTM v.16 for bridges crossing fault ruptures.

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CHAPTER 1: STATEMENT OF RESEARCH

1.1. Introduction

According to Caltrans, the Design Seismic Hazards (DSH) that are considered in the design of any bridge in California are ground shaking, liquefaction, lateral spreading, surface fault rupture, and tsunami. However, the method of considering surface fault rupture defined by Caltrans is tedious and directly dependent on the assistance of a geologist's professional judgment. In bridge design, if avoiding a fault rupture zone is not possible, there are few structural design methods defined to establish the demand on the structure due to such hazard (Caltrans, 2010). Currently, extensive procedures are used, such as site-specific seismological studies to define spatially varying ground motions and nonlinear response history analysis (RHA). These methods are required in the design of lifeline bridges crossing fault rupture zones but may be considered too onerous for what Caltrans refers to as Ordinary Standard Bridges defined in Section 1.1 of Caltrans Seismic Design Criteria (SDC).

The scope of this research is to achieve a method of analysis used for seismic design of bridges crossing surface rupture zones that is rooted in structural dynamics theory, rational, and convenient enough for application in design of "ordinary" bridges. Investigative goals included reviewing the simplified method derived in previous research, validating its use in a wide variety of applications, and ensuring its proper automated integration into user-friendly software for simplicity of utilization in design.

1.2. Current Problem

Within California, some existing bridges, including highway overpasses, span across a fault trace or are within the bounds of an identified fault rupture zone. Within the context of this thesis, a fault rupture zone considers a series of surface fractures spread out over a zone of unknown width where a distinct fault rupture line may not reach the surface. As more fault rupture lines are identified, and the approximation of enveloping hazard width continues to increase, construction of bridges across fault ruptures is becoming less avoidable. Evidence of bridge damage due to actual fault-ruptures provides estimations of support displacements and bent drift demands imposed in the bridge. A simple and accessible analysis method that enables fault-rupture demand to be considered in the design of bridges in these locations may aid in the prevention of these damages in the future.

1.2.1. Evidence of Damage

Bridge damage due to spanning earthquake fault ruptures are evident in various reconnaissance reports and is recognized as a neglected hazard in bridge design (Bray, 2001). A combination of differential vertical offset and lateral translation due to surface rupture along the Chelungpu Fault ripped through buildings and infrastructure along its nearly 90 meter fault trace in the Chi-Chi, Taiwan Earthquake on September 21, 1999. The Wu Hsi Bridge, which consists of two paralleling bridges facilitating traffic in each direction, was traversed by up to 2 meters of faulting between piers. The northbound bridge had robust piers that moved with the ground, unseating the deck, whereas the southbound bridge had

weaker piers that failed in shear saving the deck from collapse (Figure 1.1a). The primary behavior of the Chelungpu Fault was vertical offset due to fault thrusting resulting in differential ground elevation in bridge supports. For example, the Shinhkang Dam was offset approximately 9 meters near the right abutment due to a dip-slip rupture in combination with ground shaking and resulted in a catastrophic failure (Figure 1.1b).

Figure 1.1 – Damage due to dip-slip rupture along the Chelungpu Fault in the 1999 Chi-Chi Earthquake (a) Wu Hsi Bridge - Northbound deck collapse (left) and the Southbound bent shear failure (right). (Image provided by NISEE e-library: The Earthquake Engineering Online Archive)
(b) Shinhkang Dam failure (Bray, 2001)

Similar structural damage from fault rupture was recorded in both the Kocaeli and Duzce earthquakes in Turkey in 1999. The Kocaeli earthquake ($M_w=7.4$) was a right-lateral, strike-slip fault that reached an average transverse offset of around 3 meters with a maximum measured vertical displacement of 2.4 meters. The Sapanca Fault rupture propagated further east later that year due to the Duzce earthquake

($M_w=7.1$) which produced up to 4 meters of right-lateral displacement with localized vertical movement. Several meters of right-lateral displacement along the surface fault rupture line passed at an oblique angle under one of the eastern spans of the Bolu Viaduct (Figure 1.2a), which is a vital highway bridge connecting the city of Duzce to Bolu. The surface rupture that traversed the span diverted around an embedded pier foundation. The differential ground displacement rotated a pier causing permanent displacement of the deck relative to its supports (Figure 1.2b). The varying strike-slip ground displacement permanently distorted the base-isolators connecting the superstructure to the piers to minimize the demand caused by uniform ground motion (Bray, 2001). Two-dimensional elevation models were used in the development of this design which did not fully capture the curved layout of the viaduct (Turer et al., 2004).

Figure 1.2 – Bolu Viaduct damage after the 1999 Kocaeli and Duzce earthquakes; (a) Overview of Viaduct running east-west (Turer et al., 2004), (b) Evidence of bent rotation due to span crossing fault rupture (Bray, 2001)

1.2.2. Software Application

The particular hazard of having a fault rupture pass underneath a bridge is unique in that the ground displacement and motion is no longer spatially uniform across the entire bridge but instead behaves in an equal and opposite direction on either side of the fault rupture (Goel et al., 2008). With many possible strike-slip fault rupture line locations and orientation angle with respect to the bridge, an automated process of quickly identifying the deck displacement and bent drift demand can assist the user in quickly identifying the orientation of greatest demand on the bridge and the magnitude of that demand. Therefore, the implementation of Fault Rupture Response Spectrum Analysis (FR-RSA) in CSiBridge™ v. 16 is a timesaving addition to the automated seismic design process previously offered by the bridge analysis software which considered only uniform ground motion.

1.1. Previous Investigations and Preliminary Research

As a direct result of the 1971 San Fernando Earthquake, the Alquist-Priolo Act of 1972 was decreed to prohibit the construction of buildings within known fault rupture zones in California with intention of decreasing property damage due to earthquake surface fault ruptures. However, construction of non-inhabitable infrastructure such as highway overpasses and bridges were not restricted by this law (Alquist-Priolo Earthquake Fault Zoning Act, 2012). Evidence of damage from the San Fernando Earthquake increased interest in research enhancing the understanding of bridge behavior associated with surface rupture crossing and resulted in increased funding from the Federal Highway Administration, California Department of Transportation and National Science

Foundation earthquake initiating the study of nonlinear seismic bridge response (Chen, 2001).

Tseng and Penzien (1975) studied inelastic flexural behavior of bent columns used a three-dimensional elasto-plastic model and also explored the discontinuous behavior of expansion joints using nonlinear mathematical modeling. More importantly, Penzien continued work with Chen in proposing a three-dimensional time-history analysis method that defined four different types of elements in creating the bridge model. Similar to some definitions used in the OpenSees model defined in this study, Penzien and Chen (1977) proposed using solid elements for the surrounding soil where the interaction between the soils and the abutments were defined by a frictional element. Also, the bridge deck, bent columns and bent caps were defined by isoparametric beam elements and the bent columns foundation flexibilities considered with applied boundary elements. With these unique definitions the effect of separation, impact and slippage at soil-abutment interfaces could be taken into account (Chen, 2001). Other studies have contributed to the advancement and application of non-linear inelastic analysis such as Ahmed (1991) that developed analytical techniques to estimate the three dimensional nonlinear inelastic seismic response of planar highway overcrossings and its practical application. Although many research achievements have been made in the last forty years pertaining to seismic analysis in bridge behavior, further study on nonlinear seismic analysis of bridges leading to simplified methods are still being discovered and refined.

More recently, studies by Goel and Chopra throughout 2008 and 2009 provided a simple approximation method that estimates the demand of bridges crossing fault ruptures. The previous method of analysis was dependent on obtaining spatially-varying ground motions through work with seismologists and computation of rigorous nonlinear response history analysis (Goel et al., 2008). Their work also considered the role of shear keys in seismic behavior of bridges crossing fault rupture zones ultimately determining that the upper bounds for estimating deck displacement can be computed by modeling the abutments with no transverse stiffness due to shear keys, and an upper bound for estimated column drift due to fault rupture can be computed by modeling the shear keys as behaving elastically. Case studies for verifying the two approximation methods proposed by Goel and Chopra to estimate the bridge demand due to fault rupture, Fault-Rupture Linear Static Analysis (FR-LSA) and Fault-Rupture Response Spectrum Analysis (FR-RSA), were initially straight three and four span bridges. In later studies three and four span curved bridges at different fault-span orientations were used to validate the approximation procedure (Goel et al., 2008). In 2012, these procedures were implemented into CSiBridgeTM and are further discussed in this study. More details on the basis of the linear and nonlinear components of this approximation procedure are discussed in Chapter 2.

CSiBridgeTM is the first integrated 3-D bridge design software to implement the FR-RSA approximation method of analysis for design of bridges crossing fault rupture zones.

Prior to its implementation in version 16 of the software, no integrated 3-D bridge design software offered the user the ability to consider the peak demand on the bridge due to the

combined quasi-static fault rupture displacement and dynamic response due to spatially varying ground motion automatically, without the tedious work of user-defined load cases.

1.2. Scope of Investigation

The entirety of the bridge crossing fault ruptures analysis approximation method investigation began prior to this thesis research. The following phases contributed to the overall investigation, although Phases 02 through 04 are contributions unique to this study.

1.2.1. Phase 01 – Application of Analysis Methods

Once the approximation methods were validated using three and four span straight bridges, case studies were selected from various three and four span curved bridges that crossed fault ruptures in California provided by Caltrans for application of the approximation method to curved bridges typical to Caltrans design. The selected bridge case studies were Bridge 55-0837S, a three span curved bridge located in the city of Anaheim, and Bridge 55-0939G, a four span curved bridge located in the city of Orange. The two analysis methods derived by Goel and Chopra, Fault-Rupture Response Spectrum Analysis (FR-RSA) and Fault-Rupture Linear Static Analysis (FR-LSA), were applied to each bridge model using the finite element software Open System for Earthquake Engineering Simulation (OpenSees). Fault-bridge orientation bounds were considered using Bridge 55-0837S and the bridge response values were compared between various methods of analysis in Rodriguez (2012). The FR-RSA method for approximating the bridge demand from crossing a

fault rupture during a seismic event was proved most adequate when applied to the aforementioned case studies.

1.2.2. Phase 02 – Identification of Baseline Results

In order to validate the application of the FR-RSA method integrated into CSiBridgeTM version 16 Beta, a baseline set of comparison results from the finite element model created in OpenSees were identified for each case study. The OpenSees bridge model coordinates are able to be rotated with respect to the fixed fault placement in order to simulate variable fault orientations with respect to the bridge. The case selected for validation of Bridge 55-0837S in CSiBridgeTM using OpenSees results was a fault rupture located equidistant from Bents 2 and 3 and running perpendicular to a chord connecting the two deck ends (Figure 1.3). This fault-bridge perpendicular orientation is considered 0° bridge rotation in the OpenSees Model (Rodriguez 2012). Two fault-rupture cases were considered for Bridge 55-0939G, each oriented perpendicular to a chord connecting the abutments. Fault A and Fault B are located at mid-span between bents 2 and 3 and bents 3 and 4, respectively (Figure 1.4). For reference in confirming adequate integration of the FR-RSA procedure, the displacement was measured at the abutments and bents of each bridge model due to the combined response of fault rupture ground displacement (quasi-static response) and both fault-parallel and fault-normal ground motion (dynamic response).

Figure 1.3 - 55-0837S Bridge Model with Fault-Bridge Orientation of 0° at Mid Span

Figure 1.4 - 55-0939G Bridge Model with both Fault A and Fault B having Fault-Bridge Orientation of 0° at mid span of each respective span

1.2.3. Phase 03 – Creation of Equivalent CSiBridgeTM Model

By default, the CSiBridgeTM Software automatically creates a finite element bridge model given user-defined parameters such as the bridge layout (deck geometry), cross-sectional and material properties, connections, and support restraints. Both

Bridge 55-0837S and Bridge 55-0939G models were created with user-defined parameters defining the actual built bridge as provided by Caltrans. Once the automatic bridge model was generated by CSiBridge™, the resulting mass and other automated properties were compared with the values defined in the OpenSees Model and modified if necessary. The fundamental period of the structure was also compared between models to confirm correct nodal mass application and similar bridge behavior. If any severe discrepancy existed between the OpenSees and CSiBridge™ models of the respective bridge, corrective modifications were induced to insured consistent properties between models. It was essential to allow CSiBridge™ to automatically generate the components within each model in order to validate the application of FR-RSA within the context of how a user would most likely utilize the application.

1.2.4. Phase 04 – Validation of CSiBridge™ FR-RSA Implementation

The FR-RSA procedures defined by Goel and Chopra (2008) were integrated into CSiBridge™ version 16 Beta as the Caltrans Fault Crossing Seismic Demand application option within the Design Request form. Before this new application can be released for use in analysis, the proper implementations of these procedures must be proved accurate. This validation of the implementation of FR-RSA into CSiBridge™ is considered in this study by comparing the accuracy of the displacement quantities of interest produced by CSiBridge™ bridge models with that of the previously proved OpenSees model displacement results. This thesis discusses the procedures and reasoning behind decisions made in creating the

equivalent CSiBridgeTM models that best capture the behavior of the bridge case studies created in OpenSees. The result comparisons are discussed and further studies suggested.

CHAPTER 2: BRIDGES CROSSING FAULT RUPTURES ANALYSIS

METHODS

2.1. Introduction:

Investigations from Goel and Chopra (2008) proved an adequate procedure to accurately estimate the seismic demands on a bridge crossing a fault-rupture zone. Two proposed approximation methods' results were compared with the “exact” bridge response generated using Response History Analysis (RHA). Although the methods were originally applied exclusively to straight bridges, the underlying theory used in developing the procedures proved them to be adequate for application on curved bridges, bridges with many spans, and bridges with varying orientation to the fault. Work by Rodriquez (2012) validated the use of these procedures as applied to a curved three-span bridge with multiple fault-bridge orientations. A summary of the two approximation methods developed by Goel and Chopra (2008), FR-RSA and FR-LSA, are described in this chapter along with conclusions from Rodriquez (2012). Results from these previous studies supply justification for implementation of the FR-RSA approximation method into the latest version of CSiBridgeTM, for use in seismic design of bridges.

2.2. Fault-Rupture Zone Ground Motion

Bridges that cross fault-rupture zones are defined as bridges whose supports are in very close proximity to a seismic fault such that if a rupture were to occur, an instant displacement, parallel to the fault could occur between two or more bridge supports. In

addition to the nonlinear displacement parallel to the fault, the bridge support would undergo seismic ground shaking in both the fault parallel and fault normal directions.

FR-RSA and FR-LSA methods provide reasonable estimates of a bridge's total response with less computational effort than RHA. The total response of the bridge is estimated by the summation of the response at each degree of freedom due to fault-rupture offset and the dynamic response in both the fault-parallel and fault-normal directions which can be represented by the equation

$$r^t = r_o^s + r_o \quad (2.1)$$

where r_o^s is the peak response due to fault rupture offset which includes the effect of gravity loads and is calculated by non-linear analysis of the bridge due to ground displacements applied at all supports, and r_o represents the peak dynamic response value. Therefore, the bridge demand, which can be extrapolated by the displacement of the bridge at any degree of freedom, can be represented by

$$u_o^t = u_o^s + u_o \quad (2.2)$$

The approximation that the total bridge response is a summation of these displacements is supported by the conclusion that the time step at which the peak dynamic displacement occurs is generally after the fault has reached and sustained its maximum displacement (Goel et al, 2008). Figure 2.1 depicts the alignment of peak value time stamps for both quasi-static (row 1) and dynamic response (row 2) histories which supports that the summation of the peak displacement values is a valid approximation for the total bridge response (row 3) because the displacements occur simultaneously.

Figure 2.1 - History of displacement due to quasi-static response, dynamic response, and total response, due to Response History Analysis (RHA) measured as displacement at (a) the abutment and (b) the column drift in the bent. The response is in the transverse direction due to fault-parallel motions on a strike slip fault (Goel et al, 2008).

For this thesis, the Caltrans SDC spectrum with 5% damping was used to approximate the peak dynamic ground motion response for fault-rupture zones. Although, the response spectrum derived by Dreger, Hurtado and Chopra (2007) for ground motions in very close proximity to the causative fault rupture was found to differ from the Caltrans SDC (shown in Figure 2.2), the disparity was negligible for these particular case studies which have bent supports over 30 meters away from the fault rupture location. For simplicity in practice, Caltrans has opted to use the response spectrum already integrated into the code for the implementation of these approximation methods.

Figure 2.2 - Graph of Caltrans SDC Spectrum in comparison with Dreger, Hurtado and Chopra's normalized 5%-damped elastic response spectrum for ground motions in the fault-parallel (FP) and fault-normal (FN) directions

The effects of spatially varying ground motion were considered by Goel and Chopra as well. Spatially-varying ground motion considers the delayed effect of dynamic ground motion as it propagates outward from the fault rupture source. If a given bridge is very long and the fault rupture occurs near the middle, the ends of the bridge may feel the ground motion some time after the event initiation. Figure 2.3a shows the displacements at 6 designated stations across a straight bridge (Goel et al., 2008). The displacement due to fault rupture and ground motion parallel to the fault is presented in Figure 2.3b and the dynamic fault-normal response is depicted in Figure 2.3c. The results from this straight bridge study due to spatially varying ground motion support that the fault motions are anti-symmetric about the fault plane. The displacements occurring at stations equidistant from the fault experience equal magnitude in opposite directions on either side of the fault in the fault-parallel direction. In addition, the displacement magnitudes are identical at every station confirming that the displacements are proportional to one another and are

unaffected by spatially-varying ground motion on such a small scale as this. Assumptions made in the derivation of the fault rupture approximation methods are rooted in these observations.

Figure 2.3 - (a) Location of stations across the fault where spatially-varying ground motions were simulated and displacements in the (b) fault-normal direction and (c) fault-parallel direction at the six stations across a strike-slip fault during magnitude 6.5 earthquake (Goel and Chopra, 2008).

2.2.1. *Ground Offset Due to Fault Rupture*

To simulate the physical ground offset that occurs with the rupture of a seismic fault, a static ground displacement is applied at each bridge support or connection with the ground. Because the earth is moving in opposite directions on either side of the fault line, the offset applied at each support is uniform in magnitude but opposite in direction on either side of the fault. For example, in Figure 2.4, all supports on the right side of the fault line are assumed to be displaced parallel to the fault line half the distance of the total fault rupture displacement, which, in this example is 1 meter. The offset applied at supports to the left of the fault share the same magnitude, 0.5 meter, but with the opposite algebraic sign or direction. Thus, the fault-rupture ground motion at any given support location l distance from the vertical strike-slip fault line can be represented by the Proportional Multiple-Support Excitation equation:

$$u_{gl}(t) = \alpha_l u_{go}(t) \quad (2.3)$$

where α_l is the proportionality constant for the support l th distance away from the fault rupture which, in this case, is +1 for all supports located on the right hand side of the fault line, and -1 for all supports located on the left hand side of the depicted fault line. Therefore, both static fault displacement step functions and dynamic ground motion response spectrums represented as a function of time, $u_{go}(t)$, can be modified to simulate proposed fault-rupture zone ground motion as a function of time, $u_{gl}(t)$, using Equation 2.3. It is noted that for bridges crossing faults with other dip or rake angles, the proportionality constant may vary from +/- 1. The

bridge response to this imposed ground offset is considered to be the Non-linear Quasi-Static Response of the bridge.

**Figure 2.4 - Plan view of Bridge 55-0837S Fault Rupture Displacement specified for CSiBridge™
Automated Fault Crossing Seismic Bridge Design**

2.2.2. Linear Analysis Theory

For linear dynamic analysis of bridges with uniform ground excitation (i.e. not crossing a fault rupture zone), a force vector that statically applies earthquake forces, called an influence vector, can be used to capture the peak dynamic response of the bridge. An example of an influence vector that could be used in the linear analyze of an ordinary straight bridge with uniform ground motion is depicted in Figure 2.5a. However, in order to obtain the maximum dynamic response of the bridge due to simultaneous ground offset and ground shaking in the

fault parallel direction, the influence vector must be in agreement with the directionality of the quasi-static response in order to amplify the total response in combining these two effects. This fault crossing static force vector is referred to as the “effective” influence vector and is depicted in Figure 2.5b. In comparing Figure 2.5a and 2.5b, it is observed that fault-rupture excites lower dynamic modes than uniform ground motion and therefore, a bridge designed to withstand the load case associated with uniform ground motion may not be adequate to withstand the unique load case that is associated with a bridge structure crossing a fault rupture. Figure 2.6 depicts the effective influence vector assumed for a curved bridge similar to Bridges 55-0837S and 55-0939G discussed in this thesis.

Figure 2.5 - Deflected shape of an “ordinary” straight bridge: (a) depicts an influence vector associated with uniform ground motion and (b) depicts the “effective” influence vector, i_{eff} , associated with strike slip fault crossing ground motion (Goel and Chopra, 2008)

Figure 2.6 - Illustration of “effective” influence vectors used for Bridge 55-0837S (a) ι_{eff}^{FP} for Fault-Parallel ground motion, (b) ι_{eff}^{FN} , for Fault-Normal ground motion

Applying the Proportional Multiple-Support Excitation equation (equation 2.3) in both the fault-parallel and fault-normal directions, the displacements at bridge support l can be represented by

$$u_{gl}^{FP}(t) = \alpha_l^{FP} u_g^{FP}(t) \quad (2.4a)$$

$$u_{gl}^{FN}(t) = \alpha_l^{FN} u_g^{FN}(t) \quad (2.4b)$$

where $u_g^{FP}(t)$ and $u_g^{FN}(t)$ are the displacement histories of motion at a reference location, and α_l^{FP} and α_l^{FN} are the proportionality constants for the l^{th} support, represented in the fault-parallel (Equation 2.4a) and fault-normal (Equation 2.4b) directions, respectively. The dynamic response of the bridge, which combines the

response due to both fault-parallel and fault-normal ground histories, can be represented on the right side of the dynamic equation of motion as

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = -\mathbf{m}\mathbf{t}_{eff}^{FP}\ddot{u}_g^{FP}(t) - \mathbf{m}\mathbf{t}_{eff}^{FN}\ddot{u}_g^{FN}(t) \quad (2.5)$$

where $\mathbf{m}$, $\mathbf{c}$ and $\mathbf{k}$ are respectively the bridge matrices for mass, damping and stiffness and $\ddot{\mathbf{u}}$, $\dot{\mathbf{u}}$, and $\mathbf{u}$, are respectively velocity, acceleration, and displacement vectors of the bridge. The “effective” influence vectors, $\mathbf{t}_{eff}^{FP}$ and $\mathbf{t}_{eff}^{FN}$, are defined for fault-parallel and fault-normal ground motion, respectively, as the vectors of displacements at all structural degrees of freedom due to simultaneous static application of unit displacements at the supports (i.e. both bent column foundations and bridge abutments) with a value equal to the associated proportionality constant, α_l^{FP} and α_l^{FN} , respectively, applied at the l^{th} support of the elastic bridge model.

2.2.3. *Non-Linear Analysis*

Bridges crossing fault-rupture zones are expected to be deformed beyond their linear-elastic range in the event of a fault rupture. Therefore, Goel and Chopra (2008) proved that Equation 2.1 and 2.2 are still adequate methods for estimating the seismic demands for “ordinary” bridges deforming into their inelastic range. To approximate the non-linear bridge displacement the quasi-static response, u_o^s , is determined by non-linear analysis of the bridge subjected to peak values of ground displacement, $\alpha_l u_{go}$, simultaneously applied at each support.

2.3. Analysis Method Procedures

2.3.1. *FR-RSA Procedure*

FR-RSA is implemented by the following procedures per Goel et al. (2012):

1. **Obtain the Design Fault Offset and Design Spectrum for the bridge site:**

The location of the fault relative to the bridge, amount of estimated fault rupture offset, and direction of the displacement is provided from Geotechnical Services (GS) or by a geotechnical consultant with GS approval. Based on the larger probabilistic and deterministic offset, the displacement of the longitudinal and transverse vector components of the Design Fault Offset can be determined. The Ground Shaking Hazard considered by Caltrans is represented in the form of a design spectrum specified in Caltrans Seismic Design Criteria (SDC) and may be considered identical in both the fault-parallel and fault-normal directions.

From these displacement values, proportionality constants, α_l^{FP} and α_l^{FN} , can be determined and thus the displacement of each support, $u_{gl}^{FP}(t)$ and $u_{gl}^{FN}(t)$, calculated.

2. **Determine the nonlinear Quasi-Static Response of the bridge due to Design**

Fault Offset: Use a nonlinear model of the bridge to capture the behavior of the bridge due to the imposed design fault offset located at the station of the fault.

This nonlinear model should include plastic hinges at bent connections and possibly nonlinear springs modeling the shear keys, abutment back wall, and

soil at the abutment base. These parameters are defined in SDC. The quasi-static response, $\mathbf{r}_{QS}^{FP}$ and $\mathbf{r}_{QS}^{FN}$, are found by application of both gravity loads and a fault offset due to fault rupture movement, u_{gl}^{FP} , as defined in Equation 2.3. The orientation of the fault will not always parallel the axis of the node of interest. Therefore, there can be an x and y component to the imposed design fault offset. The quasi-static response of the bridge is, therefore, captured in both the transverse and longitudinal directions.

3. **Determine the Dynamic Response of the Structure:** Compute the vibration periods, T_n , and mode shapes, ϕ_n , of the bridge considering as many modes as necessary to capture the full dynamic response of the bridge which was found to be approximately 18 to 24 modes. From these, compute the fault-rupture effective influence vectors, $\mathbf{t}_{eff}^{FP}$ and $\mathbf{t}_{eff}^{FN}$, as vectors of displacements at all structural degrees of freedom due to the simultaneous static application of support displacements, α_i^{FP} and α_i^{FN} . Determine the modal participation factors in the fault-parallel and fault-normal directions using equations 2.9 and 2.10. Compute the response to the n^{th} mode, $\mathbf{r}_n^{FP}$ and $\mathbf{r}_n^{FN}$, due to fault-parallel and fault-normal ground shaking using dynamic modal analysis and modal participation factors. Lastly, combine the modal responses from each mode, $\mathbf{r}_n^{FP}$ and $\mathbf{r}_n^{FN}$, using complete quadratic combination (CQC) procedure to obtain the peak dynamic response, $\mathbf{r}_o^{FP}$ and $\mathbf{r}_o^{FN}$, due to fault-parallel and fault-normal ground hazards, respectively.

4. Combine the Static and Dynamic Responses to Obtain the Total Seismic

Demand: The total seismic demand estimated for a bridge crossing a fault rupture zone is ultimately determined by the summation of the peak bridge response values from static fault rupture offset and dynamic ground shaking components, represented as:

$$\mathbf{r}_o^t = |\mathbf{r}_{QS}^{FP}| + |\mathbf{r}_{QS}^{FN}| + \mathbf{r}_o^{FP} + \mathbf{r}_o^{FN} \quad (2.5)$$

2.3.2. LSA Procedure

The LSA (Linear Static Analysis) procedure is the simplest approximation because it avoids calculating the bridge modes of vibration by conservatively estimating the dynamic response associated with RSA to a static analysis of the bridge for appropriately selected forces reflecting the one most dominant bridge mode. In using LSA to approximate the total bridge response of a bridge crossing a fault rupture zone, Step 1 and Step 2 are identical to that of the RSA procedure. Modified Steps 3 and 4 are described below per Goel et al. (2012).

1. Obtain the Design Fault Offset and Design Spectrum for the Bridge Site

2. Determine the nonlinear Quasi-Static Response of the bridge due to Design Fault Offset

3. Determine the Dynamic Response of the Structure: Considering only the most dominant dynamic mode of the bridge structure, the peak dynamic response can be estimated here by a static analysis of the linear model due to lateral forces in the fault-parallel and fault-normal directions whose magnitude is determined by $\mathbf{m}\mathbf{t}_{eff}^{FP}A_{max}^{FP}$ and $\mathbf{m}\mathbf{t}_{eff}^{FN}A_{max}^{FN}$, respectively, where $\mathbf{m}$ represents the entire mass matrix, $\mathbf{t}_{eff}^{FP}$ and $\mathbf{t}_{eff}^{FN}$ are the fault rupture influence vectors computed from linear elastic analysis of the bridge, and A_{max}^{FP} and A_{max}^{FN} are the peak values of the spectral acceleration for ground hazard in the fault-parallel and fault-normal directions, respectively. If the peak values of the spectral acceleration for ground hazard are not readily available, they can be approximated using $A_{max}^{FP} = 2.5\ddot{u}_{go}^{FP}$ and $A_{max}^{FN} = 2.5\ddot{u}_{go}^{FN}$.

4. Combine the Static and Dynamic Responses to Obtain the Total Seismic

Demand: The total response is, therefore, computed as Equation 2.6.

$$\mathbf{r}_o^t = \max of \begin{bmatrix} \mathbf{r}_{QS}^{FP} + \mathbf{r}_{QS}^{FN} + \mathbf{r}_o^{FP} + \mathbf{r}_o^{FN} \\ \mathbf{r}_{QS}^{FP} + \mathbf{r}_{QS}^{FN} + \mathbf{r}_o^{FP} - \mathbf{r}_o^{FN} \\ \mathbf{r}_{QS}^{FP} + \mathbf{r}_{QS}^{FN} - \mathbf{r}_o^{FP} + \mathbf{r}_o^{FN} \\ \mathbf{r}_{QS}^{FP} + \mathbf{r}_{QS}^{FN} - \mathbf{r}_o^{FP} - \mathbf{r}_o^{FN} \end{bmatrix} \quad (2.6)$$

2.3.3. Approximation Method Implemented into CSiBridgeTM

The results comparing the seismic demand estimated by RHA, FR-RSA and FR-LSA on straight and curved bridges from Goel and Chopra (2008) and Rodriguez et

al (2012), respectively, proved FR-RSA and FR-LSA to be both valid for analysis of bridge crossing fault ruptures; however the FR-RSA provides more accurate predictions than FR-LSA when compared to the “exact” RHA procedure. Therefore, this thesis focuses only on implementation of FR-RSA on CSiBridgeTM.

CHAPTER 3: FINITE ELEMENT BRIDGE MODELS

3.1. Introduction

Previous to this thesis, the FR-RSA procedure for bridges crossing fault rupture zones was implemented in OpenSees and was confirmed to be adequate through analysis of two case studies; a three-span curved bridge designated as Bridge 55-0837S in California (Rodriguez, 2012) and another four-span curved bridge designated as Bridge 55-0939G also in California. This chapter provides details of the two bridges and the development of analytical models for application of FR-RSA procedures in CSiBridge™ version 16 Beta.

3.2. Description of Considered Bridges

3.2.1. Case Study I: Bridge 55-0837S

The curved bridge, designated as Bridge 55-0837S, serves as a major onramp to Interstate 5 from the amusement park, Disneyland, in Anaheim, California. This Caltrans Bridge is a pre-stressed post tension concrete continuous structure constructed in the year 2000 that exemplifies Caltrans typical design practices for many ordinary bridges throughout California. Bridge 55-0837S has three spans with four support restraints; the south end abutment, the bent column foundation located at the median of the interstate, the bent column foundation located on the interstate shoulder, and the north end abutment. Each of these supports are represented in the OpenSees model as Abutment 1, Bent 2, Bent 3 and Abutment 4, respectively as shown Figure 3.1. The structure facilitates two lanes of traffic with over 200,000

traffic vehicles a day. Its total length is 15.13 meters with a vertical clearance of 5.63 meters and 60.1 meters maximum span over 10 lanes of Interstate 5 traffic (City-data, 2010).

Figure 3.1 - Plan view and elevation of Bridge 55-0837S
(Photos adapted from Google Street View)

3.2.2. Case Study II: Bridge 55-0939G

Bridge 55-0939G is a four-span bridge that serves as a junction overpass for westbound traffic from Highway 22 merging northbound on Highway 55 in the city of Orange in southern California. It consists of two lanes with an out-to-out width of 12.8 meters (42.0ft) and facilitates approximately 34,800 total vehicles per day of which 14,000 are trucks. The pre-stressed concrete box-girder bridge was constructed in 2001 by the State Highway Agency. The bridge overpass spans ten lanes of traffic with a maximum span length of 62 meters (203.4ft) between Bents 3 and 4 identified in Figure 3.2 (City-data, 2012).

Figure 3.2 - Plan view and elevation of Bridge 55-0939G
(Photos adapted from Google Street View)

3.3. Simplifications and Assumptions for the Selected Bridges

Within the OpenSees models, bridge geometry, boundary conditions and materiality were simplified by engineering assumptions as described below. While the OpenSees models were not developed or investigated in this thesis, it is important to introduce the assumptions and simplifications used in development of these models to help the readers understand the model development in CSiBridgeTM that will be presented in Chapter 4. In OpenSees, the bridge components were modeled with a series of nodes; each assigned coordinates in a three-dimensional space and connected with property-defined member elements. Simplifications made include omitting the deck grade and assigning the deck geometry to a level elevation, fixing the bent tops to the deck with an ideally rigid connection, and reducing the support restraints to an assumed elastic behavioral stiffness. The OpenSees models of both Bridge 55-0837S and Bridge 55-0939G were originally developed by the researchers from the University of California at Irvine (UCI) for other

research purposes. The UCI models were then modified to be linear and nonlinear for use in the FR-RSA procedure. Consistent with the procedures described in Section 2, the linear model is used in the eigenvalue analysis for extraction of modal information of the bridge that is required in the FR-RSA procedure to estimate both the fault-parallel and fault-normal peak dynamic responses of the bridge. See Appendix A for the periods of vibration and mode shapes associated with each case study's respective linear model. The nonlinear bridge models are used in the FR-RSA procedure to estimate the response of the bridge due to quasi-static fault rupture offset when pushed to the inelastic range of deformation.

3.3.1. Nodal Coordinates and Orientation

The curved bridge superstructure is composed of multiple spans each subdivided into 10 linear elements that model the behavioral properties of the bridge deck section by approximating a curved geometry. Similarly, each bent column is represented by 5 elements whose lengths are defined by equally subdividing the respective bent lengths. Therefore, Bridge 55-0837S has 30 total deck elements and 10 total bent elements, whereas the Bridge 55-0939G consists of 40 total deck elements and 15 total bent elements. Figure 3.3 graphs the nodal coordinates and connecting elements along the Y-Z axis (plan view) and X-Z axis (elevation view) which define both Bridge 55-0837S and Bridge 55-0939G in OpenSees. In the linear bridge models, the bridge deck and bents are composed of elastic beam-column elements (i.e., `elasticBeamColumn` in OpenSees) connecting each node. The nonlinear model is identical to the linear model with exception of being able to

capture the non-linear behavior of the bents. The bents in the nonlinear model are defined as nonlinear beam-column elements with distributed plasticity and linear curvature distribution (i.e., dispBeamColumn in OpenSees).

(a) Case Study I: Bridge 55-0837S

(b) Case Study II: Bridge 55-0939G

Figure 3.3 – Graph of the nodal coordinates in plan and elevation of Bridge Case Study finite element models as defined in OpenSees.

The importance of measuring the displacement at the abutment ends is to consider the magnitude of the deck's potential impact with the abutment back wall and shear keys. Therefore, the orientation of the node coordinates in the OpenSees model are oriented perpendicular to the tangent of the deck curve at the abutments. For ease of computation, the bent nodes for Bridge 55-0837S were oriented parallel to Abutment 1 node. All other deck element nodes are oriented to the global coordinate system. For Bridge 55-0939G, the bent column foundations are considered fixed. Therefore, the orientations of the bent nodes are in parallel to the global coordinate system. In Figure 3.4 and 3.5, the nodal local axis orientations are depicted for reference in interpreting the displacement results in Chapter 7 which are given in the local axis longitudinal, u_1 , and transverse, u_2 , directions.

(a) Bridge Plan View

(b) Abutment 1

(c) Bent 2

(d) Bent 3

(e) Abutment 4

Figure 3.4 - Bridge 55-0837S: Local Axis orientations where u1 is the Local Longitudinal Axis and u2 is the Local Transverse Axis.

(a) Plan View

(b) Abutment 1

(c) Abutment 5

Figure 3.5 - Bridge 55-0939G: Local Axis orientations where u_1 is the Local Longitudinal Axis and u_2 is the Local Transverse Axis.

3.3.2. *Element Cross-Sectional Properties*

The material and cross-section properties assigned to these beam- column elements are derived from the bridge geometry and idealized for the deck and bent columns based on behavioral properties specific to each case study as summarized in Table 3.1. From the weight of the material and the tributary area associated with the adjacent member elements, a mass value is assigned at each node along the deck and bent columns at all translational and rotational degrees of freedom for use in calculating the fundamental period of the bridge in dynamic analysis. Assuming the effect of reduced stiffness due to cracking of the concrete, a reduced bent column

cross-section is considered in analysis by applying the stiffness reduction factor obtained from the Caltrans Seismic Design Manual (Figure 3.6).

Table 3.1 - Sumamry of Case Study Cross-sectional and Matiral Properties

Section & Material Properties		Case Study I		Case Study II		Units
		Deck	Bents	Deck	Bents	
Cross-sectional Area	A	7.6293	5.8965	7.4899	3.4636	m ²
Moment of Inertia about U2	I ₂	5.9499	2.7668	6.5033	0.9546	m ⁴
Moment of Inertia about U3	I ₃	47.157	2.7668	67.563	0.9546	m ⁴
Torsional Constant	J	0.2099	5.5335	0.1054	1.9093	m ⁴
Poisson's Ratio	V	0.2	0.2	0.2	0.2	
Modulus of Elasticity	E	27606.2	27606.2	27606.2	27606.2	Mpa
Shear Modulus	G	23005.17	23005.17	23005.17	23005.17	Mpa

Figure 3.6 - Effective Stiffness of Circular Cracked Reinforced Concrete Sections (Caltrans SDC, 2010)

3.3.3. *Bent and Abutment Restraints*

It was assumed that the restraint behavior of the soil surrounding a shallow bent foundation could be modeled by an elastic spring with a stiffness representative of the soil properties although this does not fully capture the inelastic behavior of the soil. The bent bases of Bridge 55-0837S are therefore modeled with elastic rotational springs and elastic translational springs with stiffnesses equal to 5.65×10^{10} kN/mm and 145 kN/mm, respectively. The springs are considered ideally rigid vertically and torsionally. Bridge 55-0939G foundations are deep and therefore chosen to be modeled as ideally rigid in all rotational and translational degrees of freedom. In addition, two identical spring elements were defined at each abutment along the local vertical, longitudinal and transverse directions to consider the soil-structure interaction and other restraining effects due to the presence of shear keys, wing walls and back walls at the abutments. Abutment soil springs were modeled as elastic and assigned stiffness values in the vertical direction consistent with the original UCI model which are 4.94×10^4 kN/mm and 6.35×10^4 kN/mm for Bridges 55-0837S and 55-0939G, respectively. In accordance to the recommendation from Caltrans Seismic Design Criteria, the abutment springs in the transverse direction is modeled as a linear elastic spring with a stiffness determined as 50% of the transverse stiffness of the adjacent bent (Caltrans, 2010). The bent stiffness value used is a combination of the elastic transverse bent column stiffness and the foundation soil spring in the transverse direction. As a result, the spring stiffness along the transverse direction at each abutment is equal to 20.93 kN/mm for both abutments in Bridge 55-0837S, and 11.595 kN/mm and 27.576

kN/mm for Bridges 55-0939G abutments 1 and 5, respectively, to account for the difference in bent stiffness from Bents 2 and 4. In the longitudinal direction, the elastic-perfectly plastic gap spring specified in the original nonlinear model was converted to an elastic compression-only spring using Caltrans SDC recommendations, shown in Figure 3.7, where the equivalent effective stiffness, K_{eff} , can be determined as

$$K_{eff} = \frac{P_{bw}}{\Delta_{eff}} = \frac{P_{bw}}{\Delta_{gap} + P_{bw}/K_{abut}} \quad (9)$$

where P_{bw} is the passive pressure force resisting movement at the abutment, and Δ_{gap} and K_{eff} are the coefficients determined from the elastic-perfectly plastic gap springs defined in the original UCI model. Conceptually, the displacement restraining effect from each abutment along its local longitudinal direction depends on the longitudinal displacement of the bridge superstructure. A larger longitudinal bridge displacement leads to more severe damages occurring at the abutments. Therefore, a smaller stiffness should be assigned to the abutment longitudinal springs to consider the less significant restraining action. The Caltrans SDC suggest a stiffness varying between 0.1 to 1.0 K_{eff} for the longitudinal abutment springs, which can be further determined from an iterative process based on the longitudinal displacement of the bridge. For the OpenSees model, $0.10K_{eff}$ was used for the abutment spring soil stiffness in the longitudinal direction resulting in the stiffness values 28.54 kN/mm and 3.658 kN/mm for Bridges 55-0837S and 55-0939G, respectively.

Figure 3.7 - Simplification of longitudinal abutment springs
(Adapted from Caltrans, 2010)

CHAPTER 4: DEVELOPMENT OF ANALYTICAL MODEL USING CSIBRIDGE™ V. 16 BETA INTEGRATED 3-D BRIDGE DESIGN SOFTWARE

4.1. Introduction

Computers and Structures, Inc. developed CSiBridge™ to be the complete integrated tool for modeling, analysis, and design of bridge structures. With versatility and productivity in mind, the CSiBridge™ design package allows engineers to quickly create bridge models with the aid of automated finite element modeling templates and enables the user to define specific design parameters that are then applied to the model during an automated cycle of analysis through design (Caltrans, 2010). This chapter describes the unique commands and specific performance sequence imperative for successful and efficient 3D bridge modeling within CSiBridge™. A summary of definitions and exceptions specific to each of the created case study models used in validating the CSiBridge™ FR-RSA application presented as the Automated Caltrans Fault Crossing Seismic Bridge Design feature is also presented. Appendix B provides greater detail and step-by-step assistance in the creation of the CSiBridge™ 55-0837S bridge model.

4.2. Navigating CSiBridge™ User Interface

In order to run analyses using CSiBridge™, a necessary sequence of construction is required to properly create a 3D bridge model per the CSiBridge™ Seismic Design Manual (Computers & Structures Inc., 2010). As a guide to navigate users, the tabs along the top row of the CSiBridge™ user interface are presented in the general sequence used in creating a bridge model (Figure 4.1). The Home tab houses all icons for navigating the

three-dimensional model and accessing the post-processor bridge response results. A bridge's physical properties are defined using the commands located in the Layout and Components tabs and configured together using the Bridge tab. Load cases and dynamic functions are defined under the Loads tab, run under the Analysis tab, and later used in automated design processes defined under the Design/Rating tab. By defining the aforementioned properties of the bridge, a finite element model will be automatically generated by the software allowing the user to specify only general constraints and properties of the known bridge without having to make a large number of finite element modeling decisions. All automatic modeling and analysis choices made by CSiBridge™ are in accordance to the Caltrans Seismic Design Criteria. If any of these automatically generated model components needs to be overridden or altered once the model is generated, the *Advanced* tab houses all manual modeling commands.

Figure 4.1 - CSiBridge™ v16 Beta User Interface Toolbars

4.2.1. Defining Bridge Properties

All CSiBridge™ bridge models begin with the definition of bridge geometries and properties that can later be utilized by different components of the bridge structure. First, the Layout Line, a line representing the centerline of the deck section in three-dimensions, is defined. The line is defined horizontally (in plan) in terms of the X and Y axis and vertically (in elevation) along the Z axis. This Layout Line can be composed of any combination of oriented curved and straight lines and is the spine

in which all other components will be applied to generate the bridge model. Next, the bridge material properties such as concrete and steel rebar are defined, either by theoretical behavioral properties or by using a provided template, for use in the definition of bridge component frame sections. Once the desired materials are defined, cross-sectional frame and cable properties are defined for bent columns, deck components, pre-stressing strands, or any other cross-section that may need to be used in the composition of the bridge. When creating these geometric frame section models, many templates are provided for different types of frames including *Other* which allows the user to define a frame section by its performance properties or by using the Section Designer interface to design a unique geometry. The Section Designer must be used to define any cross-sections with more than one material, such as concrete bent columns with longitudinal and confining reinforcing steel, for use in nonlinear analysis.

4.2.2. Creating a Bridge Object

Once the properties of each component are defined, the superstructure and substructures can be identified and compiled into a Bridge Object. This Bridge Object maps the organization of the bridge components and their location and, once completely defined, is the source from which the software generates the final bridge model. The superstructure component is defined by the deck cross-section and any parametric variation the deck might experience throughout its length. Many typical box girder, tee beam and steel girder templates can be selected and modified to achieve the desired geometry and material properties in modeling the bridge deck.

The substructure components include bearings, restrainers, foundation springs, abutments, and bents which are individually defined and later assigned accordingly within the Bridge Object. In defining a Bridge Object under the *Bridge* tab, the superstructure is identified and applied along the layout line, span lengths are specified and bents and abutments assigned accordingly. Once all the defined bridge components are assigned relationships within the Bridge Object, the finite element bridge model will be automatically generated and appear within the interface working space as shown in Figure 4.2. Many additional modeling assumptions are made at this time by the CSiBridge™ automatic model generation. Although the user may define a generic model constraint in the Bridge Object, such as defining the bent Girder Support Condition as *Integrated* or selecting *Foundation Spring* when specifying the abutment Substructure Type, CSiBridge™ will interpret these constraints and automatically generate the links and FE elements necessary to achieve the behavior desired within the model. For example, CSiBridge™ models the foundation springs at the abutments of the bridge superstructure with two locations of a series of links that represent the interaction between the superstructure, bearing, and soil as explicitly identified in Figure 4.2. Once the Bridge Object is created, these automatically generated links can be accessed under the *Components* tab and modified if necessary. Because the Bridge Object essentially associates the location and definition of each component with respect to each other, the Auto Update function, when selected, will automatically update the bridge model if any dependent property identified within the Bridge Object is modified. However, if any component of the bridge model is manually overridden

using the commands in the *Advanced* tab, the previous default constraints will be reinstated each time the Update function is selected. Therefore, if the user is manually altering small details within the FE model, it is best to keep the Auto Update function unselected.

Figure 4.2 - Bridge Object Component Identification

4.2.3. Bridge Analysis and Output Data

Once the bridge model is defined by the user and the three-dimensional finite element model is automatically created within CSiBridgeTM, many analyses can be performed. Vehicular loads along with other load patterns, including dead and live loads, can be applied to the structure. Seismic functions, such as Response Spectrum and Time History, can also be defined for use in seismic analysis. Next,

Load Cases including static pushover, nonlinear staged construction, modal, response spectrum, and many others, can be defined and run under the *Analysis* tab. However, for precision, efficiency and user ease, an Automated Seismic Design Request can be created instead, under the *Design/Rating* tab, in which all necessary load cases and load combinations are automatically generated and analyzed with a bridge bent demand output. This process is discussed further in Section 5.2. When designating Caltrans Fault Crossing as the bridge design request type for the Automated Seismic Design Request, the FR-RSA method (discussed in Chapter 2) is automatically executed to determine the seismic demand on each bent column in both the transverse and longitudinal directions due to a designated fault rupture. Details of this CSiBridgeTM v.16 Beta feature are discussed in Section 5.3. Using the icons located in the Display section under the *Home* tab, the deformed bridge shape resulting from each load case and combined load cases can be viewed along with tables presenting all bridge properties, definitions, analysis result quantities and design data (Figure 4.3). Within the Analysis Result tables, displacement quantities at every joint throughout the bridge can be output for every load case created. The Design Data tables provide quantities calculated for the bridge bent column force demand, capacity, idealized moment, and cracked properties.

Figure 4.3 – CSiBridge™ Analysis Result Output Tables

4.3. Case Study I: Definition of Bridge 55-0837S in CSiBridge™

This section describes the Bridge 55-0837S CSiBridge™ model used to validate the correct application of the FR-RSA procedures in CSiBridge™ version 16 Beta by comparing the results from Automated Caltrans Fault Crossing Seismic Design with the OpenSees' Bridge 55-0837S model FR-RSA results. When generating the bridge model in CSiBridge™, the priority was to precisely replicate the modeling choices used in the OpenSees model while also respecting the default automatic settings provided by CSiBridge™. Throughout the Bridge 55-0837S model building process, some of the automated bridge creation functions offered in CSiBridge™ were overridden to ensure consistency with the OpenSees model while other model discrepancies were left

unchanged because they were found trivial or unable to be overridden within the user interface of CSiBridge™. These incongruent properties among finite element models are disclosed and further discussed in Chapter 6.4. Within the following section, the CSiBridge™ modeling procedure introduced in Section 4.2 is reiterated with respect to the particular definitions used in creating the Case Study I model. Although this section is only a summary of the created CSiBridge™ model, a step-by-step tutorial for replicating the Case Study I model is provided in Appendix B.

4.3.1. Property Definitions

The material properties defined within the Bridge 55-0837S CSiBridge™ model are presented in Table 4.1. The geometry of this case study was simplified in the creation of the OpenSees model and, therefore, requires only two defined cross-sections, the circular bent column cross-section, applied at both bents, and the box girder bridge deck cross-section applied as the superstructure.

Table 4.1 - Properties of Materials Defined in CSiBridge™

Material Properties		Deck / Cover Concrete	Core Concrete	Rebar Steel
Material Type	-	Concrete	Concrete	Rebar
Weight per Unit Volume	-	17.2796	17.2796	76.9729
Units	-	KN, m, C	KN, m, C	KN, m, C
Modulus of Elasticity	E	2.76E+07	2.76E+07	2.00E+08
Poisson's Ratio	U	0.2	0.2	-
Coefficient of Thermal Expansion	A	9.90E-06	9.90E-06	1.17E-05
Specified Concrete Comp. Strength	f'c	34500	45000	-
Minimum Yield Stress	Fy	-	-	475000
Minimum Tensile Stress	Fu	-	-	620528.2
Expected Yield Stress	Fye	-	-	455054
Expected Tensile Stress	Fue	-	-	682581

The bent column Frame Section was created using the Section Designer application to custom define the column material properties, reinforcement, and confinement (Figure 4.4a). Instead of applying a General Frame Section to the bent columns, which assigns only the desired stiffness properties without need of further specifications, it was crucial to accurately model the bent reinforcement in order to achieve precise I-cracked and plastic hinge models that are automatically calculated by CSiBridgeTM in the inelastic quasi-static fault rupture pushover component of FR-RSA. The bent cross-section details were specified in California Department of Transportation 55-0837S official plans (Figure 4.4b). The material properties applied to the column section were the core concrete and cover concrete materials used in the OpenSees model, applied accordingly. Table 4.2 compares the cross-section geometry and stiffness properties defined in the OpenSees model with the CSiBridgeTM bent cross-section properties resulting from the simplification of the detailed confined concrete section created using the Section Designer application. The comparison supports that bent properties specified in CSiBridgeTM are sufficiently similar to those of OpenSees for use in analysis validation.

(a)

(b)

Figure 4.4 - Bridge 55-0837S: Bent Column Section Comparison; (a) CSiBridge™ Section Designer (b) California Department of Transportation 55-0837S Detail

Table 4.2 - Bridge 55-0837S: Bent Frame Section Properties as calculated prior to axial loading

Section Property	OpenSees Model	CSiBridge™ Model	Units
Cross-sectional Area	5.8965	5.8723	m ²
Torsional Constant	5.5335	5.488	m ⁴
Moment of Inertia about U3	2.7668	2.7442	m ⁴
Moment of Inertia about U2	2.7668	2.7442	m ⁴

It is the design of CSiBridge™ that the deck cross-section can be geometrically specified using the provided superstructure templates located under the *Components* tab, which automatically calculates generalized deck stiffness properties and applies the deck along the defined Layout Line as the superstructure within the Bridge Object. However, when defining the deck section geometry for this case as specified by the California Department of Transportation 55-0837S official plans,

the automatically calculated deck stiffness properties from CSiBridgeTM were not consistent with those assigned in the OpenSees model. To ensure congruency in deck properties among models, a Frame Section defining the general deck properties was created and manually applied to the layout line that overwrites the automatically applied Bridge Object superstructure. The resulting assigned deck properties for the manually modified model are represented in Table 4.3. A full discussion of the defined deck frame section used in this model is presented in Section 4.5.

Table 4.3 - Bridge 55-0837S: Deck Frame Section Properties

Section Property	OpenSees Model	CSiBridgeTM Model	Units
Cross-sectional Area	7.6293	7.6293	m ²
Torsional Constant	0.2099	0.2099	m ⁴
Moment of Inertia about U3	5.95	5.95	m ⁴
Moment of Inertia about U2	47.16	47.16	m ⁴

4.3.2. Bridge Object

The Bridge Layout Line for Bridge 55-037S was created by identifying the location and orientation of each deck segment between neighboring nodes. These parameters were extracted from the nodal information used in creating the OpenSees model.

Figure 4.5 shows the CSiBridgeTM format in which these nodes are specified.

Thirty-one layout line nodes were specified, all located at zero vertical elevation.

Bridge Layout Line - Horizontal Layout Data

Bridge Layout Line Name: Coordinate System: Quick Start Templates:

Layout Line Segment Data

Layout Line Segment Type	Station m	Radius m	Bearing PI to EC
Initial Station and Bearing	0.		S690000E
1 Straight at New Bearing To Station	4.6015		S690000E
2 Straight at New Bearing To Station	9.203		S690000E
3 Straight at New Bearing To Station	13.8045		S700000E
4 Straight at New Bearing To Station	18.4058		S720000E
5 Straight at New Bearing To Station	23.0072		S730000E
6 Straight at New Bearing To Station	27.6085		S750000E
7 Straight at New Bearing To Station	32.2099		S760000E
8 Straight at New Bearing To Station	36.8112		S760000E

For quick editing of an existing segment right click either a table row or a segment in the sketch below.

Layout Line Plan View (X-Y Projection) (Double Click Picture For Enlarged View)

Units:

Station: Bearing:

Radius: Grade:

X: Y: Z:

Figure 4.5 - Bridge 55-0837S: CSiBridge™ Bridge Horizontal Layout Line definition

Once the layout line is defined, the Bridge Object Data is specified; the deck is applied along the Bridge Layout Line, the bridge abutments are designated at the end of the layout line, and the bents are designated to the appropriate location or station along the layout line as seen in Figure 4.6. The properties of the bents assigned in this Bridge Object included the length, which is 10.7 meters for Bent 2 and 11 meters for Bent 3, column Frame Section as described in Section 4.3.1, and behavior and length of the bearing between the bent top and superstructure, which is 1.68 meters with a fully fixed integrated bent cap for Bridge 55-0837S.

Figure 4.6- Bridge 55-0837S: CSiBridge™ Bridge Object assignments

4.3.3. Bridge Restraints

At the abutment locations, the spring stiffness coefficients were user defined according to Table 4.4 to match those values discussed in Section 3.2.3 and assigned to the Bridge Object. Each soil spring was oriented along the local axis of the respective node in which it was assigned, depicted in Figure 3.4 in which the u2 axis and the u1 axis respectively represent the transverse and longitudinal directions at each node. The bent soil spring restraints are automatically assigned at the bottom node of each bent column. Figure 4.7 illustrates the plan view and elevation

of the bridge model developed in CSiBridgeTM. As shown, node assignments, boundary conditions, and geometries of the model match the model developed in OpenSees as seen in Figure 3.3a.

Table 4.4 - Bridge 55-0837S: Soil Spring stiffness assigned along the nodal Local Axis

Type	Direction	Abutment Soil Spring Stiffness		Bent Foundation Soil Spring	
		Release Type	Stiffness (kN/mm)	Release Type	Stiffness (kN/mm)
Translation	Vertical	Partial Fixity	49400	Fixed	5.65E+10
	Longitudinal	Partial Fixity	2.854	Partial Fixity	145
	Transverse	Partial Fixity	10.465	Partial Fixity	145
Rotation	Vertical	Free	0	Partial Fixity	56500
	Longitudinal	Free	0	Partial Fixity	56500
	Transverse	Free	0	Partial Fixity	56500

Figure 4.7 - Bridge 55-0837S: Plan and Elevation of CSiBridgeTM model (Screen Shots from CSiBridgeTM Interface)

4.4. Case Study II: Definition of Bridge 55-0939G in CSiBridge™

While the approach to constructing the Bridge 55-0939G model using the CSiBridge™ software is similar to that of Bridge 55-0837S, the property definitions defined by the OpenSees model in Section 3.2 are entirely unique to this four-span bridge. The procedures and commands for replicating the Case Study I model detailed in Appendix B are also generally valid for the construction of this Case Study II if definitions of properties and overall geometry is altered accordingly.

4.4.1. Property Definitions

The materials summarized in Table 4.1 are identical for both Case Studies I and II. Similarly, the bent frame sections were specified using the CSiBridge™ Section Designer function (Figure 4.8a). Although the bent cross-sections of the built Bridge 55-0939G are hexagonal (Figure 4.8b), a circular bent cross-section was assumed in the OpenSees model for simplicity in symmetrical moments of inertia. For use in the inelastic model, the bent sections are defined with longitudinal reinforcing and confining steel as specified by the California Department of Transportation 55-0930G details, depicted in Figure 4.8b. Moreover, if the cover is considered spalled in the nonlinear model and not contributing to the resisting capacity of the column, the outer geometry is trivial and a circular geometry can be assumed. The defined reinforcing details of each bent column cross-section are summarized in

Table 4.5. The general frame section properties used in the elastic model are compared between the OpenSees and CSiBridge™ models in Table 4.6 to ensure congruency between models.

(a)

(b)

**Figure 4.8 – Bridge 55-0939G: Bent Column Section Comparison; (a) CSiBridge™ Section Designer
(b) California Department of Transportation 55-0939G Detail**

Table 4.5 - Bridge 55-0939G: CSiBridge™ Section Designer specifications

Geometry			
Height (m)	2.1		
Width (m)	2.1		
No. of Cores	1		
No. of Rings	1		
Rings			
Bent No.	2	3	4
Cover (m)	0.05	0.05	0.05
No. of Bundles	32	34	28
Bundle Type	1	1	2
Bundle Bar No.	45M	45M	45M
Bundle Material	Rebar 55-0939G	Rebar 55-0939G	Rebar 55-0939G
Conf. Type	Spiral	Spiral	Hoops
Conf. Spacing (m)	0.065	0.065	0.075
Conf. Bar No.	20M	20M	25M
Concrete Model			
Conf. Material	Rebar 55-0939G		
Material	Core 55-0939G		
Core Concrete	Core1		
Other Concrete	Mander-Unconfined		
Outer Concrete	Mander-Unconfined		

Table 4.6 – Bridge 55-0939G: Bent Frame Section Properties

Section Property	OpenSees Model	CSiBridge™ Model	Units
Cross-sectional Area	3.4636	3.4414	m ²
Torsional Constant	1.9093	1.8848	m ⁴
Moment of Inertia about U3	0.9547	0.9425	m ⁴
Moment of Inertia about U2	0.9547	0.9425	m ⁴

As mentioned previously, a complex deck section can be specified as a Bridge Object component and its generalized deck stiffness properties will automatically be calculated and applied along the defined Layout Line as the bridge superstructure. However, when defining the deck section geometry for this case as specified by the California Department of Transportation 55-0939G official plans, the automatically calculated deck stiffness properties from CSiBridge™ were not consistent with those assigned in the OpenSees model. To ensure congruency in deck properties among models, a Frame Section defining the deck properties with defined Deck Concrete material was created and manually applied to the layout line that overwrites the automatically applied Bridge Object superstructure. A full discussion of the defined deck frame section used in this model is discussed in Section 4.5. The resulting assigned deck properties for the manually modified model are represented in Table 4.7, below.

Table 4.7 – Bridge 55-0939G: Deck Frame Section Properties

Section Property	OpenSees Model	CSiBridge™ Model	Units
Cross-sectional Area	7.4899	7.4899	m ²
Torsional Constant	0.1054	0.1054	m ⁴
Moment of Inertia about U3	6.5033	6.5033	m ⁴
Moment of Inertia about U2	67.563	67.563	m ⁴

4.4.2. Bridge Object

The Bridge Layout Line for Bridge 55-0939G was created by identifying the location and orientation of each deck segment between neighboring nodes. These parameters were extracted from the nodal information used in creating the OpenSees model. Figure 4.9 shows the CSiBridge™ format in which these nodes are specified. Forty-one layout line nodes were specified, all located at zero vertical elevation.

Bridge Layout Line - Horizontal Layout Data

Bridge Layout Line Name: 55-0939G

Coordinate System: GLOBAL

Quick Start Templates: Quick Start...

Layout Line Segment Data

	Layout Line Segment Type	Station m	Radius m	Bearing PI to EC
1	Initial Station and Bearing	0.		S720000E
2	Straight at New Bearing To Station	3.8997		S730000E
3	Straight at New Bearing To Station	7.7994		S740000E
4	Straight at New Bearing To Station	11.6991		S750000E
5	Straight at New Bearing To Station	15.5988		S750000E
6	Straight at New Bearing To Station	19.4985		S760000E
7	Straight at New Bearing To Station	23.3982		S770000E
8	Straight at New Bearing To Station	27.2979		S780000E

For quick editing of an existing segment right click either a table row or a segment in the sketch below.

Layout Line Plan View (X-Y Projection) (Double Click Picture For Enlarged View)

Units: KN, m, C

Station: 0.
Bearing: S 73°00'00" E
Radius: Infinite
Grade: 0. %
X: 0.
Y: 0.
Z: 0.

OK
Cancel
Refresh Plot

Figure 4.9 - Bridge 55-0939G: CSiBridge™ Bridge Horizontal Layout Line definition

The Bridge Object for Case Study II, as shown Figure 4.10, is comprised of four spans distinguished by three bents of different lengths and frame section components. The bents are assumed to have a fixed connection between the bent column and superstructure with an ideally rigid bent cap defined as a frame section with extremely high stiffness. The distance between the top bent column node to the Bridge Object Layout Line is 1.57 meters. Bent 2, Bent 3 and Bent 4 have the column lengths of 8.8 meters, 7.7 meters and 7.1 meters, respectively.

Bridge Object Data

Bridge Object Name: 55-0939G
 Layout Line Name: 55-0939G
 Coordinate System: GLOBAL
 Units: Kip, in, F

Define Bridge Object Reference Line

Span Label	Station in	Span Type
Start Abutment	0.	Start Abutment
Span1	1535.3136	Full Span to End Bent
Span2	3627.1176	Full Span to End Bent
Span3	6074.1216	Full Span to End Bent
Span To End Abutment	7473.2712	Full Span to End Abutment

Note: 1. Bridge object location is based on bridge section insertion point following specified layout line.

Bridge Object Plan View (X-Y Projection)

North

Y

X

Show Enlarged Sketch...

Modify/Show Assignments

- Spans
- User Discretization Points
- Abutments
- Bents
- In-Span Hinges (Expansion Jt.)
- In-Span Cross Diaphragms
- Superelevation
- Prestress Tendons
- Girder Rebar
- Staged Construction Groups
- Point Load Assigns
- Line Load Assigns

OK Cancel

Figure 4.10 - Bridge 55-0939G: CSiBridge™ Bridge Object assignments

4.4.3. Bridge Restraints

For each abutment and bent assignment within the Bridge Object, support restraints are identified. Because the built Case Study II has a deep pile foundation, the OpenSees model originally modeled the bent column foundation with 12 meter long piles with a specific stiffness. Because CSiBridgeTM requires a bent column support restraint to be defined in the form of a foundation spring located at the bent base, the Case Study II CSiBridgeTM model used a fully fixed restraint condition at the bent base. The OpenSees model was modified to match this constraint to ensure congruency between models. At the abutments, the soil spring stiffness was considered free in the longitudinal direction, partially stiff in the vertical direction and to each have a different partial stiffness in the transverse direction due to the Seismic Design Criteria which is explained in greater detail in Section 3.2.3. Table 4.8 summarizes the stiffness values assigned to each abutment oriented along the respective local axis as identified in Figure 3.5 where the u2 axis and the u1 axis respectively represent the transverse and longitudinal directions at each node. Figure 4.11 illustrates the final plan view and elevation of the Case Study II bridge model developed in CSiBridgeTM. As shown, node assignments, boundary conditions, and geometries of the model are the same as that developed in OpenSees seen in Figure 3.3b.

Table 4.8 - Bridge 55-0939G: Soil Spring stiffness assigned along the nodal Local Axis

Type	Direction	Abutment Soil Spring Stiffness			Bent Foundation Soil Spring	
		Release Type	A1 Stiffness (kN/mm)	A5 Stiffness (kN/mm)	Release Type	Stiffness (kN/mm)
Translation	Vertical	Partial Fixity	63475.	63475.	Fixed	1.0E+14
	Longitudinal	Free	0	0	Fixed	1.0E+14
	Transverse	Partial Fixity	11.595	27.576	Fixed	1.0E+14
Rotation	Vertical	Free	0	0	Fixed	1.0E+14
	Longitudinal	Free	0	0	Fixed	1.0E+14
	Transverse	Free	0	0	Fixed	1.0E+14

Figure 4.11 - Bridge 55-0939G: Plan and Elevation of CSiBridge™ model (Screen Shots from CSiBridge™ Interface)

4.5. Manually Overwritten Automated Parameters

Once the Bridge Object is defined, the finite element model is instantaneously generated and a three-dimensional representation of the bridge model can be viewed in the viewport. This is the advantage of the CSiBridge™ structural analysis software, that the default settings and automatic assignments reduce the chance of human errors in programming. However, in comparing the parameters of this post-processor automatically generated model to that of the manually programmed OpenSees models for

the respective case studies, some automated features of CSiBridge™ default parameters were incongruent with the OpenSees model and, therefore, needed to be manually modified. The following incongruences were identified between the baseline OpenSees finite element model and the automatically generated CSiBridge™ model and were manually overwritten as such:

1. The automated bridge Superstructure generated by the Caltrans details was overwritten with a general frame section component defined with the deck section properties used in the OpenSees model.
2. Axes at abutment and bent nodes were manually rotated from the Global axis to a unique Local Axis defined in Figure 3.4 and Figure 3.5.
3. The link modeling the behavior of the bearing between the bent top and deck was modified to be ideally rigid in all degrees of freedom.
4. Lumped masses automatically generated by tributary area at all joints were zeroed and manually assigned mass quantities equal to that used in the OpenSees model.

Originally, the designated superstructure in the CSiBridge™ model was defined by the geometry specified in each case study's respective California Department of Transportation details, as shown in Figure 4.12. However, the stiffness properties of this Superstructure cross-section were not congruent to those of the OpenSees model and therefore needed to be changed. It was decided that a general frame section taking on the OpenSees' Superstructure stiffness properties would be created and assigned as a frame section to override the existing model superstructure section, depicted in Figure 4.13. By doing this, the automatically generated bearing connections (links) to the superstructure

that were geometrically dependent would remain at default with only the behavior of the bridge deck being corrected for comparison purpose. Table 4.9 and demonstrate the need for overriding the stiffness properties in each case study CSiBridge™ model to ensure congruent bridge deck behavior for response verification.

Figure 4.12 - Bridge 55-0939G: CSiBridge™ Superstructure cross-section as specified in California Department of Transportation 55-0939G Details

Property Data

Section Name

Properties

Cross-section (axial) area	<input type="text" value="7.4899"/>	Section modulus about 3 axis	<input type="text" value="6.1468"/>
Torsional constant	<input type="text" value="0.1054"/>	Section modulus about 2 axis	<input type="text" value="9.7584"/>
Moment of Inertia about 3 axis	<input type="text" value="6.5033"/>	Plastic modulus about 3 axis	<input type="text" value="5.0853"/>
Moment of Inertia about 2 axis	<input type="text" value="67.563"/>	Plastic modulus about 2 axis	<input type="text" value="16.5052"/>
Shear area in 2 direction	<input type="text" value="7.4899"/>	Radius of Gyration about 3 axis	<input type="text" value="0.9534"/>
Shear area in 3 direction	<input type="text" value="7.4899"/>	Radius of Gyration about 2 axis	<input type="text" value="3.1426"/>

Figure 4.13 - Bridge 55-0939G: CSiBridge™ user-defined deck general frame section

Table 4.9 – Case Study I: Deck Stiffness Comparison

Section Property	CSiBridge™ Model		OpenSees Model	Units
	Automatic	Manual		
Cross-sectional Area	6.2214	7.6293	7.6293	m ²
Torsional Constant	10.5348	0.2099	0.2099	m ⁴
Moment of Inertia about U3	5.2682	5.95	5.95	m ⁴
Moment of Inertia about U2	41.9038	47.16	47.16	m ⁴

Table 4.10 – Bridge 55-0939G: Deck Stiffness Comparison

Section Property	CSiBridge™ Model		OpenSees Model	Units
	Automatic	Manual		
Cross-sectional Area	6.3092	7.4899	7.4899	m ²
Torsional Constant	14.6452	0.1054	0.1054	m ⁴
Moment of Inertia about U3	5.7349	6.5033	6.5033	m ⁴
Moment of Inertia about U2	62.3076	67.563	67.563	m ⁴

Although the girder bearing, where bent top connection with the superstructure, was specified in the bridge object as *Integrated* implying a fixed bearing, the automatically

generated bearing link assigned by CSiBridge™ was a link that was fixed translationally but free to move rotationally. While this may be a better model for the actual behavior of the constructed case study bridge, the OpenSees model had considered the bearing fixed in all six degrees of freedom such that the displacement due to any load case measured at the bent top node and the corresponding deck node would be identical. Because this was not the case for the automatically generated CSiBridge™ model bridge behavior, the link properties were modified to be fixed in all degrees of freedom to ensure that the displacement values obtained for comparison between models for validation would be as similar as possible. When defining the bearing as fixed, however, the *Fixed* box cannot be checked but instead a very high stiffness value must be specified as seen in Figure 4.14.

Linear Link/Support Directional Properties

Link/Support Name
BBRG1-2

Directional Control

Direction	Fixed
☒ U1	☐
☒ U2	☐
☒ U3	☐
☒ R1	☐
☒ R2	☐
☒ R3	☐

Stiffness Values Used For All Load Cases

☒ Stiffness Is Uncoupled ☐ Stiffness Is Coupled

U1	U2	U3	R1	R2	R3
1.000E+14	1.000E+14	1.000E+14	1.000E+14	1.000E+14	1.000E+14

Damping Values Used For All Load Cases

☒ Damping Is Uncoupled ☐ Damping Is Coupled

U1	U2	U3	R1	R2	R3
0.	0.	0.	0.	0.	0.

Shear Distance from End J

U2 0.

U3 0.

Units
N, m, C

Figure 4.14 – CSiBridge™ Link Stiffness Properties modified for deck bearings at bent tops

Even with the bridge superstructure overridden with congruent frame section cross-sectional area, the automatically generated masses distributed to each joint according to the adjacent element's cross-sectional area and defined material density did not match the series of lumped masses designated to the corresponding node in the OpenSees bridge model. Therefore, the masses in the CSiBridgeTM model were set equal to zero and the mass values used in the OpenSees model were assigned manually to each corresponding node. To override the masses assigned to the bridge model, a Property Modifier multiplier of 0 was applied to the Mass of all frame sections assigned to the Bridge Object. The modification window from the CSiBridgeTM interface is shown in Figure 4.15. Once zeroed, each node along the deck and bent columns was selected and assigned mass in all three translational degrees of freedom with quantities equal to that applied to the corresponding node in OpenSees. No rotational mass was assigned. Only mass, not weight, can be manually assigned to each node using the CSiBridgeTM software. Weight must be present in the model to properly perform dead load analysis and to calculate the correct reduced bent cross-section in inelastic analysis which is a function of axial load. Therefore, the weight Property Modifier was kept equal to 1, as shown in Figure 4.15, which enabled CSiBridgeTM to automatically assign weight based on material density and tributary area to the model. Table 4.11 Table 4.12 compare the difference in total weight and mass between models which supports the modification made. It is noted that although there is a discrepancy in the total weight of the bridge models, the weight is used only in calculating the effects of dead load and is less significant in the overall response comparison, whereas the mass of the structure is used

in the dynamic load case and eigenvalue analysis case which have a greater effect on the total response.

Figure 4.15 - Mass Modification of Frame Sections set equal to zero

Table 4.11 – Bridge 55-0837S: Comparison of Total Weight and Total Mass assignments

	CSiBridge™ Model		OpenSees Model	Units
	Automated Superstructure	Manually Assigned Deck Section & Lumped Mass		
Total Weight	16491.67	23309.76	29907.28	kN
Total Mass	1681.68	3051.44	3051.44	kN.s ² /m

Table 4.12 – Bridge 55-0939G: Comparison of Total Weight and Total Mass assignments

	CSiBridge™ Model		OpenSees Model	Units
	Automated Superstructure	Manually Assigned Deck Section & Lumped Mass		
Total Weight	18704.61	25975.50	34556.82	kN
Total Mass	1763.72	3525.99	3525.99	kN.s ² /m

CHAPTER 5: CSIBRIDGETM AUTOMATED SEISMIC BRIDGE DESIGN

5.1. Introduction

The application of FR-RSA in OpenSees does not have a conventional graphic user interface and may be too onerous and complicated for practicing engineers which may limit the widespread acceptance of the analysis procedure. Therefore, an urgent need exists in the bridge design community to incorporate FR-RSA into some existing bridge analysis and design platforms in which practicing bridge engineers are familiar with. To this end, the research team collaborated with Computers and Structures, Inc. and embedded the FR-RSA method as a Caltrans Fault Crossing analysis component in the Automated Seismic Design function in CSiBridgeTM version 16. Figure 5.1 shows the CSiBridgeTM Automated Seismic Design Request window in which the Caltrans Fault Crossing can be selected and specified. Many iterations, or builds, of version 16 have been composed by Computers and Structures, Inc. over the past year and researchers from multiple universities have been able to work with the application and give feedback and suggestions for improvement. The construction and analysis of bridge Case Studies I and II, as discussed in this study, were performed in build “W” of CSiBridgeTM version 16 Beta.

As discussed in Chapter 2, the FR-RSA procedure was confirmed to be adequate through analysis of two actual curved bridges representative in California and was recommended for future design. In Chapters 3 and 4 the validated OpenSees models were described and the translation of these models into the CSiBridge^{eTM} interface was explored. This chapter

summarizes the CSiBridge™ version 15 Automated Seismic Design features, describes the characteristics of the FR-RSA procedure implemented as a Caltrans Fault Crossing type of Automated Seismic Design in version 16 of the software, and discusses the use of Ritz Vectors throughout the various analyses and ultimately the usefulness and robustness of the analysis feature as implemented.

Bridge Design Request - Fault Crossing Seismic

Name

Notes

Bridge Object

Check Type

Design Request Parameters

Fault Definition

☒ **Planar**

☐ **General Displacement Loading**

Loading

Direction	Displacement	R.S. Function
Parallel Fault Displacement	0.5	SDC Spectrum
Normal Fault Displacement	0.	None
Vertical Fault Displacement	0.	None
Parallel Uniform Acceleration		None
Normal Uniform Acceleration		SDC Spectrum
Vertical Uniform Acceleration		None

Figure 5.1 - Command being validated: Added Caltrans Fault Crossing Automated Seismic Design Type presented as an option within Bridge Design Request parameters

5.2. Automated Seismic Design

Previous to the implementation of the FR-RSA procedure in version 16, CSiBridge™ has been used by Caltrans engineers to aid in the design of bridge projects by utilizing the CSiBridge™ Automated Seismic Bridge Design function. Once the bridge model is created, this feature automates the response spectrum and pushover analysis to determine the demand and capacity displacements and then generates the demand/capacity ratios for the Earthquake Resisting System (ERS). This process aids in the design of bridges by allowing engineers to define specific seismic design parameters that are then applied to the bridge model during an automated cycle of analysis through design. By incorporating the AASHTO Guide Specification for LRFD Seismic Bridge Design, the CSiBridge™ feature provides an efficient and accurate analysis option for quick design iterations (Computers and Structure, Inc., 2010). A flow chart of the series of actions performed by the feature is organized in Figure 5.2. A summary of the operations associated with this function is discussed in this section.

Figure 5.2 - CSiBridge™ Automated Seismic Bridge Design Process

Knowing the actions performed by the Automated Seismic Design feature of CSiBridge™, a greater understanding of the additional implemented feature concerning fault rupture can be obtained. First, the Automated Seismic Design process begins with creating a bridge model as discussed in Chapter 4. Next, the desired ground motion is designated by either utilizing the imbedded location based hazard maps to generate a relevant Demand Response Spectrum, by manually defining a response spectrum per Caltrans SDC, or by specifying time history ground motions. With this information designated, a Seismic Design Request can be created to initiate the automated process. The window to create this request is located in the Seismic Design section under the *Design/Rating* tab as shown in Figure 5.3, below. The Design Request Parameters associated with the Design Request are automatically assigned per AASHTO Guide Specifications but can be viewed and/or modified in the window represented as Figure 5.4.

Loading	
Direction	R.S. Function
Horizontal	Target Spectrum
Vertical	None

Figure 5.3 - General Automatic Seismic Design Request window in CSiBridge™

Substructure Seismic Design Request Parameters

	Item	Value
1	Seismic Design Category	D
2	Bent Displacement Demand Factor	1.
3	Gravity Load-Case Option	Auto: Entire Structure
4	Gravity Load Case	
5	Additional Group	None
6	Include P-Delta	No
7	Cracked Property Option	Program Determined
8	Convergence Tolerance	1.000E-03
9	Maximum Number of Iterations	3
10	Accept Unconverged Results	Yes
11	Modal Load-Case Option	Program Determined
12	Modal Load Case	
13	Type of Modes	Ritz
14	Additional Number Of Modes	0
15	Response Spectrum Load-Case Option	Program Determined
16	Response-Spectrum Load Case	
17	Directional Combination	Absolute
18	Foundation Group	None
19	Pushover Target Displacement Ratio	4.
20	Bent Failure Criterion	Pushover Curve Drop
21	Pushover Curve Drop Tolerance	0.01

Item Description

Explanation of Color Coding for Values

Blue: All selected items are program determined

Black: Some selected items are user defined

Red: Value that has changed during the current session

Set To Prog Determined (Default) Values

All Items Selected Items

Reset To Previous Values

All Items Selected Items

OK Cancel

Figure 5.4 - Seismic Design Parameters form in CSiBridge™

Running the Design Request initiates the automated creation of various Load Patterns and Load Cases. These Load Patterns include Dead, Gravity used for dynamic analysis, and pushover analysis in the longitudinal and transverse direction for each bent. Using these Load Patterns, various Load Cases considering modal, response spectrum, linear static and nonlinear static, analyses are created in accordance with AASHTO Guide Specifications (Computers and Structures, Inc., 2010). Response spectrum load cases are automatically generated which separately apply the dynamic loads in the transverse direction, longitudinal direction and a third case with a Directional Combination scale factor of 0.3. This third response spectrum load is combined using the 100/30 percent rule

in each of the major directions. More on these specific load cases is available in Computers and Structures, Inc., 2010. In order to run these load cases and determine the displacement capacity of the bridge, the bent column plastic hinge lengths and properties are identified per AASHTO Seismic Guide Specification, Section 4.11.6. The nonlinear hinge properties are consistent with the AASHTO/Caltrans idealized bilinear moment-curvature diagram, as shown in Figure 5.5.

Figure 5.5 - AASHTO/Caltrans idealized bilinear moment-curvature diagram

As both this curve and the axial load in the bent column change throughout the pushover due overturning effects, the yield moments, plastic moments, and $I_{cracked}$ properties are determined by the automated function. The bridge seismic capacity displacement is then determined using either the implicit capacity or a pushover capacity analysis depending on the Seismic Design Category (SDC) A through D, which is determined automatically or manually by the user. Once the demand displacement and displacement capacity are complete, CSiBridgeTM computes the ratio of the Demand/Capacity displacements and reports these values in the Seismic Design Report. An example table of reported D/C ratios is provided in Figure 5.6. The Generalized Displacement, seen in Figure 5.6, reports the relative displacement between the bent caps and foundations by taking the translational difference between both points and subtracting out the displacement due to rotation. The CSiBridgeTM definition of this bent drift, GD , can be calculated as:

$$GD = U_t - U_b - \frac{L(R_t + R_b)}{2} \quad (5.1)$$

where U_t and U_b are the translational displacement at the bent top and bottom ends, respectively; R_t and R_b are the rotations at the bent top and bottom ends, respectively; and L is the length of the bent.

	DesReqName	BridgeObj Text	DCategory	SpanName Text	Station m	Direction Text	GenDispl Text	Demand m	Capacity m	DCRatio Unitless
▶	500mm	BOBJ1	D	Span1	46.01392	TRANS	<500mm>GD_TR1	0.23972	0.299527	0.8003
	500mm	BOBJ1	D	Span1	46.01392	LONG	<500mm>GD_LG1	0.093154	0.135936	0.6117
	500mm	BOBJ1	D	Span2	107.44416	TRANS	<500mm>GD_TR2	0.187248	0.238882	0.7839
	500mm	BOBJ1	D	Span2	107.44416	LONG	<500mm>GD_LG2	0.249178	0.267797	0.9305

Figure 5.6 - D/C Displacement Ratio Output from CSiBridgeTM Automated Seismic Design

5.3. Automated Caltrans Fault Crossing Seismic Bridge Design

In implementing the FR-RSA procedure (Goel et al. 2008) into CSiBridge™, the load cases unique to capturing the response of bridges crossing fault ruptures were implemented as modifications and additions to the Automated Seismic Design function as described in Section 5.2. This FR-RSA is presented in CSiBridge™ version 16 Beta as an Automated Caltrans Fault Crossing Seismic Bridge Design function selected from the drop down window shown in Figure 5.1. The implementation and use of the new Automated Caltrans Fault Crossing Seismic Design is discussed in this section along with its particular application to the Case Studies used in its validation.

5.3.1. Seismic Design Request

When creating a Seismic Design Request, as shown in Figure 5.1, this Caltrans Fault Crossing seismic bridge design function can be selected and a fault location, orientation, rupture displacement and response spectrum must be specified. In the seismic design request specified for the considered case studies, the fault orientation *Default* sets the fault rupture line perpendicular to the layout line at the station, or deck node location, at which it crosses. All design requests considered for bridge models 55-0837S and 55-0939G were assigned a fault definition orientation of 90 which sets the fault rupture line parallel to the global y-axis. For Case Study I, one Design Request was created to consider the location of a fault running equidistant between bents 2 and 3, as represented in Figures 1.4, whereas Case Study II considered two fault rupture locations, one between bents 2 and 3 and one between bents 3 and 4, with two separate Design Requests as depicted in Figure 1.5. As

described in Chapter 2, in order to consider the total bridge response due to fault rupture, a distance in which the fault offsets must be specified for calculating the demand on the bridge. This offset value is attained by consultation with Geotechnical Services. For all design requests created in this study the desired total fault rupture offset was 1 meter, therefore, the Parallel Fault Displacement was specified in all Design Requests as 0.5 meters which is imposed in opposite directions at each bent, as stated in Figure 5.1 and depicted in Figure 5.7. In accordance with the FR-RSA procedure, the dynamic response of the bridge in both the fault parallel and fault normal directions is considered. Therefore, in all Design Requests, the design spectrum defined by Caltrans SDC was specified as the Response Spectrum used in both fault-parallel and fault-normal dynamic analysis.

**Figure 5.7 - Plan view of Bridge 55-0837S Fault Rupture Displacement specified for CSiBridge™
Automated Fault Crossing Seismic Bridge Design**

5.3.2. Response Components

Consistent with FR-RSA, the Automated Fault Crossing Seismic Design function calculates the displacement demands on the bridge by combining the quasi-static response due to fault offset and the peak dynamic responses due to the fault-parallel and fault-normal ground motions through response spectrum analysis. Initially, a gravity load case is performed on the model to determine the cracked section properties for use in the load case analyses that determines the bridge responses caused fault-parallel and fault-normal ground motions (i.e. Ritz Modal Load Cases). Figure 5.8 shows the load cases as created in CSiBridge™ to generate the Combined Response of a Bridge Object.

Figure 5.8 - CSiBridge™ v.16 Response Combination

A nonlinear Quasi-static Load Case first applies the fault rupture displacement to the nonlinear bridge model to produce the quasi-static results. The Ritz Model Load

Cases, in both the fault-parallel and fault-normal orientations, approximate the periods of vibration of the bridge by assuming load-dependent Ritz vectors (Chopra, 2012). Response spectrum analysis is then used to estimate the bridge peak dynamic response caused by fault-parallel and fault-normal ground motions, respectively. For comparison with eigenvector mode shapes used in analysis in OpenSees, Appendix A provides the fundamental periods and assumed Ritz vectors associated with both Fault-Parallel and Fault-Normal Ritz Modal Load Cases for both case studies. Lastly, the Fault-Parallel Response and Fault-Normal Response, which are designated in CSiBridgeTM as load cases RS_DIS and RS_UNIF respectively, are automatically combined and output as the dynamic bridge demand in both the transverse and longitudinal directions, which is defined as the cboRSP load combination. The total combined bridge response considered, combines the cboRSP load combination with the quasi-static fault rupture displacement load case, output at DIS, to estimate the peak demands on the bridge.

CHAPTER 6: VALIDATION OF FR-RSA IMPLEMENTATION

6.1. Introduction

To validate the Caltrans Fault Crossing Seismic Design application added to CSiBridgeTM v.16, the bridge response results obtained from OpenSees and the CSiBridgeTM for each respective case study model was compared. In this section, the response quantities selected for use in validation are described and other variables and constraints associated with the validation process are discussed. It is to be noted that the Automated Seismic Design features incorporated in CSiBridgeTM version 15 are assumed to have been validated by Computers and Structures, Inc. Therefore, the validation discussed in this chapter is concerned only with the accuracy of the FR-RSA procedures embedded in CSiBridgeTM Automated Seismic Design, which will be offered in version 16 as a Seismic Bridge Design Request Type (Figure 5.1).

6.2. Validation Method

Validation of the added seismic design function was approached by comparing the Fault Rupture Response Spectrum Analysis results from the Case Studies I and II modeled in CSiBridgeTM version 16 beta build “W” and those results from the same bridges modeled in OpenSees as defined in Chapters 3 and 4. Using the OpenSees models that were modified from the models originally constructed by researchers of the University of California at Irvine, the FR-RSA approximation method was applied and the estimated response of the bridge, recorded. Based the engineering assumptions and modifications made to the OpenSees model, the CSiBridgeTM model was created as such to best emulate the behavior of the OpenSees bridge model. However, the automated bridge

model construction features offered by CSiBridgeTM were used when at all possible to ensure the corrected implementation of the FR-RSA procedure when default settings are used by CSiBridgeTM users.

6.2.1. Response Quantities of Interest

The response quantities of interest that were compared in these case studies as a means of validating the Caltrans Fault Crossing Seismic Design Request added to CSiBridgeTM v.16 were the displacements at the abutments and at the top and bottom ends of each bent. Abutment displacements were measured as the average change in length of the pair of soil springs acting at each abutment in the local transverse and local longitudinal directions. For Bridge 55-0837S, the displacement at the bent tops and bent foundations were compared in both the local transverse and local longitudinal directions. For Bridge 55-0939G, however, the bent tops are compared along the global axis and the bent foundations are not compared because they are modeled as fixed supports; therefore, the displacement measured at the bent bases is 0.5 meters in the transverse direction for the quasi-static response only, making a comparison unnecessary. It is recognized that OpenSees uses fiber elements with distributed plasticity and CSiBridgeTM uses beam-column elements with lumped plasticity, each to capture the nonlinear bent behavior. While these two types of elements provide very similar results for translational displacement quantities, they produce disparities in angles of rotation at the ends of the bents resulting in less comparable values of bent drifts when calculated according to the drift equation defined in CSiBridgeTM which takes into account the angles of

rotation at the ends of each bent. Therefore, the comparisons of the bent drifts are not used for validation in this report. To better observe the difference in the results from OpenSees and CSiBridgeTM, comparisons were made for the response quantities of each components summing to the Combined Response. Accordingly, a total of thirty-six result comparisons are presented for Case Study I including displacements in both the transverse and longitudinal directions at the two abutments and each end of the two bents from the quasi-static fault offset response, the combined dynamic response from fault-parallel and fault-normal dynamic responses, and the total response as a summation of both static and dynamic responses. For Case Study II, sixty result comparisons are presented, thirty for each fault location, A and B, which includes displacements in both the transverse and longitudinal directions at the two abutments and at the tops of the three bents from the quasi-static fault offset response, the combined dynamic response from fault-parallel and fault-normal dynamic responses, and the total response as a summation of both static and dynamic responses.

6.2.2. Troubleshooting Methods

Checks were made to ensure that the bridge case study models created in OpenSees and CSiBridgeTM were compatible for result comparison. After defining the bridge geometry and assigning the material and cross-sectional properties to the CSiBridgeTM model, the fundamental period of the structure was compared. From the comparison of period duration and primary mode shapes, errors could be found in the CSiBridgeTM model. For example, if the period calculated by CSiBridgeTM

was longer or shorter than that of the OpenSees bridge model, the stiffness of each bridge component was investigated.

Errors such as incorrectly assigned abutment soil spring stiffness due to an unknown rotation the local axis and incorrect units for assigned mass values were illuminated by the result of incongruent periods between models. By comparing mode shapes and Ritz vectors it was found that, initially, the axis about which the moment of inertia for the deck section was assigned was switched longitudinally and transversely. Common sense checks, such as ensuring the bent bottom of a fixed bent foundation moved 0.5m in the transverse direction due to the quasi-static load case, exposed for one iteration of Case Study II that, although the resultant displacement measured at the bent bottoms was equal to 0.5m, the transverse displacement was less than 0.5m and the longitudinal displacement was greater than 0 leading to the conclusion that the “default” fault orientation of the FR-RSA application was running perpendicular the tangent of the deck curve at the crossing station which was incongruent with the fault orientation assigned in OpenSees.

6.3. Use of Ritz Vectors in CSiBridgeTM

The Caltrans Fault Crossing Automated Seismic Design function integrated into CSiBridgeTM allows the user to use only Ritz Vectors instead of Eigenvalues in the dynamic analysis of a bridge model. Computers and Structures, Inc. assumes that the use of Ritz Vectors for ground displacement loading estimates the response of bridges crossing fault rupture zones better than Eigenvalues acceleration loading because it tends to excite higher frequency modes by considering first the modes that are most easily excited by the fault-rupture force distribution (Computers and Structures, 2012). It is noted that the automated modal load case using Ritz Vectors in CSiBridgeTM uses stiffness associated with the cracked property effects derived by the auto-gravity load case whereas the eigenvalues used in OpenSees apply user-defined reduction factors to bent section stiffness properties to account for cracking (Computers and Structures, Inc., 2010). Eigenvalue analysis in CSiBridgeTM uses an unreduced bent stiffness resulting in a shorter fundamental period (Tables A.1 and A.2). However, congruency of periods and mode shapes between Ritz Vectors in CSiBridgeTM and Eigenvalues in OpenSees confirm similar dynamic behavior between models and thus validate the comparison of total response results found by the implementation of the FR-RSA approximation method (Figures A.1, A.2, A.4, and A.5). The assumed Ritz vectors and approximate periods of vibration associated with each mode for both Bridges 55-0837S and 55-0939G are presented in Appendix A and discussion of their comparison to the mode shapes generated by exact eigenvalue analysis in OpenSees are discussed further in Chapter 8. The theory of Ritz Vectors is reviewed in Appendix C.

CHAPTER 7: RESULT COMPARISON AND CONCLUSIONS

7.1. Introduction

As rooted in the FR-RSA procedure, which is reviewed in detail in Chapter 2, the total displacement demands on a bridge crossing fault ruptures is estimated by the combination of the peak response values respectively caused by fault offset and both fault-parallel and fault-normal ground motions. Therefore, it is important and necessary to evaluate the adequacy of CSiBridgeTM in estimating the total bridge response as well as each individual response component. Accordingly, for each case study, fault location, and node of interest, the total combined response is compared along with separate comparisons of its two components, the quasi-static response and dynamic response, along the transverse and longitudinal directions. In addition, each case study comparison is discussed and the overall validation and usefulness of the FR-RSA procedure implementation on CSiBridgeTM is considered.

7.2. Validation Comparison Results

Figures Figure 7.1 through Figure 7.7 are graphical comparisons of the bridge response results output from CSiBridgeTM to those from OpenSees for each case study and fault location. In these figures, the relative or absolute displacement is graphed along the y-axis for the abutment and bents, respectively. The x-axis defines the abutment number or bent number being compared. First, the total response of the bridge is reported, followed by comparisons of each component summing to the total response, the quasi-static response and total dynamic response. The quasi-static response is a result of a 0.5 meter static fault offset with locations identifies in Figures 1.4 and 1.5 and is compared in both

the transverse and longitudinal direction. The dynamic response is a summation of both the fault-parallel and fault-normal dynamic responses and is also compared in both the transverse and longitudinal directions. For node and local axis identification referenced in these comparison graphs, refer to Figures 3.1, 3.2, 3.4 and 3.5. It is noted that the specific bridge responses quantities for all three case comparisons are provided in Appendix D.

7.3. Case Study I: Bridge 55-0837S Results

7.3.1. Discussion of Results

Overall, the execution of the FR-RSA application implemented in CSiBridge™ estimated a similar total combined bridge response of that calculated using OpenSees for Case Study I. When assessing the contribution of the quasi-static and dynamic responses to the slight error in the total response comparison, both components contributed fairly equal to the discrepancy. The slight differences observed in the result comparisons, which are acceptable for practical applications, are primarily due to discrepancies in the period of vibration, compared in Appendix A, and in inelastic modeling assumptions made in each model.

7.3.2. Result Comparison Graphs

(a) Total Response

(b) Quasi-static Response

(c) Dynamic Response

Figure 7.1 - Bridge 55-0837S Relative Abutment Displacement

(a) Total Response

(b) Quasi-static Response

(c) Dynamic Response

Figure 7.2 - Bridge 55-0837S Absolute Displacement at Bent Tops

(a) Total Response

(b) Quasi-static Response

(c) Dynamic Response

Figure 7.3 - Bridge 55-0837S Absolute Displacement at Bent Base

7.4. Case Study II: Bridge 55-0939G

7.4.1. Discussion of Results

In general, the use of the FR-RSA application implemented in CSiBridgeTM as applied to the four span Bridge 55-0939G model, similarly estimated the total bridge response to that of OpenSees, although not as robustly as the three span Bridge 55-0837S model. The use of the CSiBridgeTM function tended to underestimate the bridge response in the transverse direction while it overestimated the response in the longitudinal direction. The majority of the contribution to this error is found in the quasi-static response. For this case study bridge, the estimated dynamic response was found to be fairly similar between approximation method applications. At the bent tops, the responses are very similar which supports the validation of the implementation of the FR-RSA procedure as applied to CSiBridgeTM. Some unknown assumptions made by the CSiBridgeTM software when automating this procedure, thus many known and unknown discrepancies between the OpenSees and CSiBridgeTM bridge models contribute to the small amount of error seen throughout the comparisons. However, the total responses estimated by the CSiBridgeTM Automated Caltrans Fault Rupture Seismic Design feature are found reasonable; therefore, the FR-RSA procedure may be accurately implemented despite the discrepancies in modeling assumptions which are amplified by the more complex four-span bridge study.

7.4.2. Result Comparison Graphs for Fault A

(a) Total Response

(b) Quasi-static Response

(c) Dynamic Response

Figure 7.4 - Fault A: Bridge 55-0939G Relative Abutment Displacement

(a) Total Response

(b) Quasi-static Response

(c) Dynamic Response

Figure 7.5 - Fault A: Bridge 55-0939G Absolute Displacement at Bent Tops

7.4.3. Result Comparison Graphs for Fault B

(a) Total Response

(b) Dynamic Response

(c) Dynamic Response

Figure 7.6 - Fault B: Bridge 55-0939G Relative Abutment Displacement

(a) Total Response

(b) Quasi-static Response

(c) Dynamic Response

Figure 7.7 - Fault B: Bridge 55-0939G Absolute Displacement at Bent Tops

7.5. Conclusions

7.5.1. Sources of Error

Although similar model discrepancies were found for both case studies between the OpenSees and CSiBridgeTM models, the presence of four spans for Bridge 55-0939G greatly amplified the response discrepancy. This difference in the estimated response due to fault rupture may not be considered an error in the implementation of the FR-RSA procedures, but rather indication that the procedure was executed with two separate sets of modeling assumptions. The bridge vibration periods were determined through eigenvalue analysis in the OpenSees model, while the bridge vibration periods in CSiBridgeTM were determined from Ritz Vector methods based on the bridge deflection resulting from the assumed force distribution. From Appendix A, where the periods and mode shapes for each case study bridge are compared, it is seen that the fundamental period of vibration from OpenSees eigenvalues and from CSiBridgeTM Ritz vector analysis is congruent for Bridge 55-0837S and slightly off for Bridge 55-0939G. Consequently, the higher fundamental period used by CSiBridgeTM for Case Study II references a lower associated acceleration value from the response spectrum for dynamic analysis, as seen in Figure 7.8, and may have resulted in the underestimated response seen in Figure 7.7c.

Figure 7.8 – Response Spectrum used in CSiBridge™ per Caltrans Seismic Design Criteria for both Case Studies I and II

Similarly, in the inelastic model used to estimate the quasi-static response the CSiBridge™ software is designed to lump the plastic hinges at a single location near the ends of the member, whereas OpenSees used fiber element method to distribute the plasticity over the whole member. In creating the Automated Seismic Design Request in CSiBridge™ the location of the lumped plastic hinge and the plastic hinge length are automatically defined according to the Caltrans SDC and is not able to be modified by the user. Therefore, no direct comparison could be made between the plastic hinges assigned in each model compared. It is believed that this discrepancy is amplified greater in the response of Bridge 55-0939G than Bridge 55-0837S because of the presence of three bents, instead of two. In the lumped plasticity method, used by CSiBridge™ per Caltrans SDC, a plastic hinge might form in a different location than that of the distributed plasticity method used in the

estimation of the inelastic response quasi-static response by OpenSees. The same amount of plastic rotation lumped higher from the bent base than another, would result in a smaller amount of displacement at the top of the bent due to a shorter arm length. In Figure 7.9Figure 7.10, the CSiBridge™ post-processor displaced shape of both non-linear bridge models are shown with a visible displaced shape after the quasi-static fault rupture load case has been implemented. In these figures, the grey line represents the initial location of the bridge deck and colored nodes at the bent bases indicate inelastic hinging where “pink” is assumed to represent yielding at a some location, L_p , and “red” is assumed to represent a fully plastic hinge that no longer has additional resisting capacity upon increased displacement. It is noted, by evidence in Figures 7.5b and 7.7b, that the quasi-static response in the transverse direction is underestimated to the left hand side of the fault, and overestimated on the right hand side.

Figure 7.9 - Bridge 55-0837S displaced shape due to quasi-static fault rupture load case where both Bent 2 and Bent 3 have evidence of yielding (Screenshot from CSiBridge™ Interface)

Figure 7.10 – Bridge 55-0939G displaced shape due to quasi-static fault rupture load case; (a) evidence of plastic hinging in Bent 2 and 3 (b) evidence of yielding in Bent 2 and plastic hinging in Bents 3 and 4

Other contributing factors to the result discrepancy between estimated responses could be attributed to minor discontinuities between compared models. For example, although the deck-bent bearing is modeled as ideally fixed in both the OpenSees and CSiBridgeTM models, the estimated displacement measured at the top of the bents was incongruent with that measured at the corresponding deck node which should have identical displacement values if, in fact, the connection between the two nodes were ideally rigid. In addition, discrepancy in total bridge weight as seen in Tables 4.11 and 4.12 would affect the axial force assumed in

CSiBridgeTM for each bent when referencing cracked cross-sectional properties that are a function of axial load. Table 7.1 exposes the incongruity in bent cross-section reduction factors used in the application of the FR-RSA procedure in OpenSees and CSiBridgeTM.

Table 7.1 – Bridge 55-0939G: Comparison of cracked bent section reduction factors, torsional constant (J) and moment of inertia (I) about axis 2 and 3, applied in the inelastic model for both OpenSees and CSiBridgeTM

	Bent 2		Bent 2		Bent 2	
	J	I2 and I3	J	I2 and I3	J	I2 and I3
OpenSees	0.2	0.40	0.2	0.45	0.2	0.50
CSiBridgeTM	0.2	0.39	0.2	0.42	0.2	0.55

7.5.2. Accuracy of Procedures

The inability for users to alter crucial properties of the CSiBridgeTM Automated Caltrans Fault Rupture Seismic Design feature, such as model analysis type and plastic hinge type, limits the usefulness of its implementation. Now knowing the limitations of the added feature in CSiBridgeTM, an alternate set of procedures for validation composed prior to the study may have been considered. For example, the OpenSees model could have been re-written to utilize Ritz Vectors instead of eigenvalues to determine the fundamental periods of each structure or plastic hinges approximated through a lumped plasticity model. In this way, a more robust comparison could have been made between each case study model built in both OpenSees and CSiBridgeTM.

7.5.3. Validation and Conclusion

Based on the results from both Bridge 55-0837S and Bridge 55-0939G, it is shown that the implementation on CSiBridgeTM can provide adequate predictions for bridge responses and can be used in future practice. It is recognized that the validation work is based on three and four span curved bridges with ground motions associated with a strike-slip earthquake fault rupture. However, based on the result comparison of Bridge 55-0939G, it is noted that the implementation of the FR-RSA procedure in CSiBridgeTM when applied to a four span bridge with higher mode effects results in a less accurate comparison. Thus, a lack of model behavior congruency raises question to the robustness of the comparison between the OpenSees and CSiBridgeTM models in this thesis. By executing the Automated Caltrans Fault Crossing Seismic Design command, the implementation of the FR-RSA procedures is determined to have been implemented correctly although the exact estimated total response was not achieved. In conclusion, to achieve an estimated demand for a bridge crossing a fault rupture zone, adequate estimations for total bridge response can be achieved through the use of the Caltrans Fault Crossing feature in CSiBridgeTM version 16 Beta.

CHAPTER 8: RECOMMENDATIONS AND SUBSEQUENT STUDY

8.1. Introduction

Once the FR-RSA procedure was verified as an accurate approximation method for estimating the total response of a bridge crossing a fault rupture, Caltrans and various academic research teams contributed input to Computers and Structure, Inc. who then implemented the method in a beta build of CSiBridge™ version 16. The first build of CSiBridge™ version 16 featuring the Automated Fault Crossing Seismic Design function was released in January of 2012 and was entitled build “H”. Iterations of the builds continued as research teams worked with the application and gave feedback to Computers and Structures, Inc. on its ease of use and versatility. The case study bridges discussed in this thesis were modeled using CSiBridge™ version 16 Beta builds “H”, “U”, “W” and ultimately “1P”. When each build was released to the verification teams, new errors and limitations were discovered, some of which were corrected in later builds. Concerning this particular study, the following feedback was contributed to the evolution of this Caltrans Fault Rupture application. In addition, the direction of subsequent study for the further application and verification of the FR-RSA procedure is proposed.

8.2. Recommendations and Proposed Improvements

Originally the Loading options in the Design Request form were limited to applying response spectrum analyses only in parallel to those directions where a fault rupture offset was also imposed as presented in Figure 8.1. With this setup, only the quasi-static response and dynamic response due to fault-parallel ground motion was considered automatically and the demand due to fault-normal ground motion had to be determined

through a user-created load case and the resulting bridge response has to be summed manually with the other two responses to achieve a total bridge response. In beta build “U”, the addition of the dynamic analysis in the fault-normal direction was automated as seen in the updated design request presented in Figure 5.1.

Bridge Design Request - Fault Crossing Seismic

Name Seismic Fault Rupture

Notes Modify/Show...

Bridge Object BOBJ1

Check Type Caltrans Fault Crossing

Design Request Parameters AASHTO Seismic Design
Caltrans Fault Crossing

Fault Definition

☒ Planar Station 271.89 Orientation Default

☐ General Displacement Loading

Loading

Direction	Displacement	R.S. Function
Horizontal/Parallel to the Fault	0.5	Caltrans SDC Spectrum
Horizontal/Normal to the Fault	0.	None
Vertical	0.	None

Figure 8.1 – Automated Caltrans Fault Crossing Seismic Design Request as presented in CSiBridge™ version 16 Beta build “H”

With each CSiBridge™ version 16 Beta build, the units in which the station of fault crossing was specified was not a reflection of the interface specified units. Therefore, the units in which the station was identified was unknown to the user until the analysis was run. Even in post-processor, the location of the fault is unstated in the results and no visual line or denotation is provided to identify the fault rupture location and orientation

in reference to the three-dimensional bridge model. Regardless of the global units specified for the interface, the fault crossing station was specified in feet in build “H” and in inches for build “W”. In beta build “1I”, the final build worked with in this thesis, the station units are dependent on the globally specified units. However, still no visual evidence of fault rupture location is present in the user-interface. This added feature would aid in assuring users that the fault-rupture location and orientation are being executed as desired, preventing possible Design Request errors.

Specified alterations to the automatic generation of Load Cases performed by the Automated Seismic Design Request are available in the *Modify/Show* button on the Design Request Form. These modification options, seen in Figure 5.4, are limited and in the case of the Caltrans Fault Crossing modification, the *Type of Modes* option for modal analysis is unable to be changed from Ritz to Modal. Although, the use of Ritz Vectors may be the preference of Caltrans and most users of the CSiBridgeTM product, the inability to verify the results against a Eigenvalues analysis, limits the ability for results to be checked and therefore may hinder the widespread use of the added feature.

8.3. Subsequent Study

Given that CSiBridgeTM adopts the AASHTO/Caltrans recommended plastic hinge assumptions, which include plastic hinge location, length, and strength-deformation relationship, ongoing work focuses to identify the most sensitive plastic hinge parameters affecting bridge responses. Such work may provide useful information for users in the scenario when other plastic hinge properties have to be used. Efforts could also be extended to further verify the CSiBridgeTM FR-RSA procedure through more complicated bridge examples (e.g. bridges under different fault locations and orientations, and bridge with different soil spring stiffness properties). In this thesis the foundation soil springs were modeled as elastic. The nonlinearity of soil behavior could be explored and applied to the FR-RSA method in further research of total bridge response.

It is recognized that the work validating the implementation of FR-RSA in CSiBridgeTM which provides adequate predictions for bridge responses is based on the ground motions associated with strike-slip earthquake fault ruptures only. While FR-RSA and FR-LSA were developed based on fundamental theories from structural dynamics and they are expected to work regardless of the type of ground motion inputs, it is of interest to further verify their adequacy using ground motions associated with other types of faults.

Additionally, the bridges selected in this investigation both include single-column bents. Research opportunities exist to further verify the validity of FR-RSA and FR-LSA for bridges with multiple-column bents.

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APPENDIX A: PERIOD OF VIBRATION AND MODE SHAPE

COMPARISON

Table A.1 - Comparison of Bridge 55-0837S Periods of Vibration

Model Program	OpenSees	CSiBridge™	CSiBridge™
Method Used	Eigenvalues	Ritz Vectors	Eigenvalues
Mode Number	Periods of Vibration (sec)		
1	0.9760	0.9765	0.8866
2	0.8372	0.9028	0.8779
3	0.8055	0.8199	0.7869
4	0.6363	0.6985	0.6957
5	0.5432	0.5359	0.5339
6	0.4135	0.4137	0.4132
7	0.3627	0.3380	0.3381
8	0.2901	0.2709	0.2689
9	0.2663	0.1744	0.1742
10	0.2442	0.1542	0.1539
11	0.2315	0.1327	0.1217
12	0.2193	0.1298	0.1185

Figure A.1 - OpenSees Mode Shapes determined by eigenvalues for Response Spectrum Analysis

Mode 1, T = 0.9765 Seconds

Mode 2, T = 0.9028 Seconds

Mode 3, T = 0.8199 Seconds

Figure A.2 - CSiBridge™ Ritz vectors and corresponding bridge periods for Response Spectrum Analysis

Mode 1, T= 0.8866 Seconds

Mode 2, T= 0.8779 Seconds

Mode 3, T= 0.7869 Seconds

Figure A.3 - CSiBridge™ Mode Shapes determined by eigenvalue analysis unused in analysis

Table A.2 - Comparison of Bridge 55-0939G Periods of Vibration for both Fault A and B

Model Program	OpenSees	CSiBridge™	CSiBridge™
Method Used	Eigenvalues	Ritz Vectors	Eigenvalues
Mode Number	Periods of Vibration (sec)		
1	0.96	0.9774	0.7943
2	0.91	0.8389	0.7125
3	0.77	0.7246	0.6326
4	0.71	0.6315	0.5837
5	0.61	0.6161	0.5409
6	0.57	0.5492	0.5116
7	0.53	0.4351	0.4215
8	0.47	0.4343	0.4155
9	0.46	0.3597	0.3429
10	0.45	0.2875	0.2722
11	0.42	0.2837	0.2700
12	0.36	0.2205	0.2112

Mode 1, T = 0.96 Seconds

Mode 2, T = 0.91 Seconds

Mode 3, T = 0.77 Seconds

Figure A.4 - OpenSees Mode Shapes determined by eigenvalues for Response Spectrum Analysis

Figure A.5 - CSiBridge™ Ritz vectors and corresponding bridge periods for Response Spectrum Analysis

Figure A.6 - CSiBridge™ Mode Shapes determined by eigenvalue analysis unused in analysis

APPENDIX B: BRIDGE 55-0837S CSiBridge™ MODEL

DETAILED MODEL DEVELOPMENT PROCESS

The following is a step-by-step description of the actions performed in the software user interface of CSiBridge™ v16 Beta build “W” to develop a desired bridge model, exemplified here using Bridge 55-0837S. In addition, the corresponding screen-capture images are provided to aid in the understanding of the described CSiBridge™ commands and instructions.

CREATING A NEW BRIDGE MODEL

- Open CSiBridge™ v.16 Beta.
 - Select *New* under the Orb drop down window to begin a new bridge model.
 - In the New Model window, set units to *kN,m,C* and select Template *Blank*.

DEFINING THE BRIDGE LAYOUT LINE

- The layout line represents the centerline of the assigned deck section.
- Create a bridge layout line by selecting the *New* icon in the Layout Line section under the *Layout* tab.
 - Name the Bridge Layout Line.
 - In the Initial and End Station Data section, denote the End Station of the 55-0837S Bridge which is 153.4066 m. (highlighted)
 - Define the curve of the Bridge 55-0837S deck by selecting *Define Horizontal Layout Data*.

- For each direction change in the bridge deck layout, a new Layout Line Segment needs to be created. The curve of Bridge 55-0837S was modeled with 30 linear segments in OpenSees; therefore, the layout line is assigned 30 *Straight to New Bearing To Station* line layout segments oriented at increasing degrees of rotation to achieve the approximate curve.

- Add Bridge 55-0837S line layout segments, defined in Table B.1, in the Bridge Layout Line – Horizontal Layout Data window.
 - Select a Layout Line Segment Type from the drop down window options.
 - Specify the Station (or location) at which that segment's ending node will be located.
 - In the Bearing window, specify the rotation of the segment with respect to the initially straight deck. First, denote the direction of rotation; in this case, *S* rotates the segment clockwise and *N* rotates the segment counterclockwise. Denote the degrees of rotation in the next two numerical place holders.
 - Insert the segment between the two abutments by selecting *Insert Below*.
 - Select *OK* when all segments have been defined.

- Vertical Layout Line Data does not need to be altered for this bridge model because the elevation of the bridge deck is constant.

- Once the desired Bridge Layout Line has been created, select *OK* to return to the main window.

Bridge Layout Line - Horizontal Layout Data

Bridge Layout Line Name: 55-0837S Coordinate System: GLOBAL Quick Start Templates: Quick Start...

Layout Line Segment Data

Layout Line Segment Type	Station m	Radius m	Bearing PI to EC
Straight at Previous Bearing To Station	0		N900000E
2 Straight at New Bearing To Station	153.4066		N900000E

For quick editing of an existing segment right click either a table row or a segment in the sketch below.

Layout Line Plan View (X-Y Projection) (Double Click Picture For Enlarged View)

Station: 0 Bearing: N 90°00'00" E Radius: Infinite Grade: 0. % X: 0 Y: 0 Z: 0

Units: KN, m, C

OK Cancel

Bridge Layout Line - Horizontal Layout Data

Bridge Layout Line Name: 55-0837S Coordinate System: GLOBAL Quick Start Templates: Quick Start...

Layout Line Segment Data

Layout Line Segment Type	Station m	Radius m	Bearing PI to EC
Straight at New Bearing To Station	32.2099		S760000E
1 Initial Station and Bearing	0		N900000E
2 Straight at New Bearing To Station	4.6015		S690000E
3 Straight at New Bearing To Station	9.203		S690000E
4 Straight at New Bearing To Station	13.8045		S700000E
5 Straight at New Bearing To Station	18.4058		S720000E
6 Straight at New Bearing To Station	23.0072		S730000E
7 Straight at New Bearing To Station	27.6085		S750000E
8 Straight at Previous Bearing To End	153.4066		S750000E

For quick editing of an existing segment right click either a table row or a segment in the sketch below.

Layout Line Plan View (X-Y Projection) (Double Click Picture For Enlarged View)

Station: 0 Bearing: S 69°00'00" E Radius: Infinite Grade: 0. % X: 0 Y: 0 Z: 0

Units: KN, m, C

OK Cancel

- In the View section under the *Home* tab, select *XY* to see the created bridge layout line in plan.
- The bridge layout line can be further edited by selecting the *Modify* icon in the Layout Line section under the *Layout* tab.

The dialog box is titled "Bridge Layout Line Data". It contains several sections for inputting bridge data:

- Bridge Layout Line Name:** 55-0837S
- Coordinate System:** GLOBAL
- Units:** KN, m, C
- Plan View (XY Projection):** A graph showing a curved line representing the bridge layout. The Y-axis is labeled "North".
- Station:** 0.0
- Bearing:** S 69°00'00" E
- Radius:** Infinite
- Grade:** 0.0 %
- X:** 0.0
- Y:** 0.0
- Z:** 0.0
- Coordinates of Initial Station:**
 - Global X: 0.0
 - Global Y: 0.0
 - Global Z: 0.0
- Initial and End Station Data:**
 - Initial Station (m): 0.0
 - Initial Bearing: N800000E
 - Initial Grade in Percent: 0.0
 - End Station (m): 153.4066
- Horizontal Layout Data:**
 - Define Horizontal Layout Data... Quick Start...
- Define Layout Data:**
 - Define Vertical Layout Data... Quick Start...
- Buttons:** OK, Cancel, Refresh Plot

Table B.1 Bridge 55-0837S Layout Line Segment Data

	Layout Line Segment Type	Station m	Bearing PI to EC
1	Initial Station and Bearing	0	S690000E
2	Straight at New Bearing To Station	4.6015	S690000E
3	Straight at New Bearing To Station	9.2030	S690000E
4	Straight at New Bearing To Station	13.8045	S700000E
5	Straight at New Bearing To Station	18.4058	S720000E
6	Straight at New Bearing To Station	23.0072	S730000E
7	Straight at New Bearing To Station	27.6085	S750000E
8	Straight at New Bearing To Station	32.2099	S760000E
9	Straight at New Bearing To Station	36.8112	S780000E
10	Straight at New Bearing To Station	41.4126	S790000E
11	Straight at New Bearing To Station	46.0139	S810000E
12	Straight at New Bearing To Station	52.1569	S830000E
13	Straight at New Bearing To Station	58.2999	S850000E
14	Straight at New Bearing To Station	64.4430	S870000E
15	Straight at New Bearing To Station	70.5860	S890000E
16	Straight at New Bearing To Station	76.7290	N890000E
17	Straight at New Bearing To Station	82.8721	N870000E
18	Straight at New Bearing To Station	89.0151	N850000E
19	Straight at New Bearing To Station	95.1581	N830000E
20	Straight at New Bearing To Station	101.3011	N810000E
21	Straight at New Bearing To Station	107.4442	N790000E
22	Straight at New Bearing To Station	112.0404	N770000E
23	Straight at New Bearing To Station	116.6367	N760000E
24	Straight at New Bearing To Station	121.2329	N740000E
25	Straight at New Bearing To Station	125.8292	N730000E
26	Straight at New Bearing To Station	130.4254	N710000E
27	Straight at New Bearing To Station	135.0216	N690000E
28	Straight at New Bearing To Station	139.6179	N680000E
29	Straight at New Bearing To Station	144.2141	N660000E
30	Straight at New Bearing To Station	148.8104	N650000E
31	Straight at Previous Bearing to End	153.4066	N650000E

DEFINING MATERIAL PROPERTIES

- The material properties used in OpenSees to model Bridge 55-0837S are defined in Table B.2.
- Create each material model by selecting *Material Properties* from the *Type* drop down window in the Properties window under the *Components* tab.
 - Select the *New* icon to create a new material.
 - In the Quick Material Definition window select the Region *United States*, Material Type as either *Concrete* or *Rebar*, and Standard as *User* for user defined.
 - Define the Material Property Data according to Table B.2.
 - Select OK to save.
 - Repeat to create all three materials.

Table B.2 Material Properties (kN, m, C)

Material Name	55-0837S Core	55-0837S Cover	55-0837S Rebar
Material Type	Concrete	Concrete	Rebar
Weight per Unit Volume	17.2796	17.2796	76.9729
Modulus of Elasticity, E	27600000	27600000	2.00E+08
Poisson's Ratio, U	0.2	0.2	-
Coeff. of Thermal Expansion, A	9.90E-06	9.90E-06	1.17E-05
Specified Concrete Comp. Strength, f'c	45000	34500	-
Minimum Yeld Stress, Fy	-	-	475000
Minimum Tensile Stress, Fu	-	-	620528.2
Expected Yield Stress, Fye	-	-	455054
Expected Tensile Stress, Fue	-	-	682581

DEFINING FRAME SECTIONS

- A frame section is any set of cross-section parameters that may be applied to any component of the bridge object. For Bridge 55-0837S, two frame sections need to be defined; the deck section and the bent column section. Both frame sections will be manually assigned properties to match those defined in the OpenSees Model.
- Create each frame section model by selecting *Frame Properties* from the *Type* drop down window in the Properties section under the *Components* tab.
 - Select the *New* icon to begin creating a new frame section.
 - Select *Other* from the Add Frame Section Property Type window to manually define section properties.
- Create the deck frame section.
 - Select *General*.
 - Set Properties as defined in Table 4.3.
 - Select *OK* to continue defining the section.
 - Name the deck frame section.
 - Define the material as *55-0837S Core*.
 - The Mass will later be applied manually at each node along the deck therefore; the Mass Property Multiplier must be set equal to 0.
 - Select *Set Modifiers*
 - Change Mass from 1 to 0 in the Frame property/Stiffness Modification Factors window. Set all other multiplies equal to 1.
 - Select *OK* to save.
 - Select *OK* to create the deck frame section.

- Create bent cap frame section to be ideally rigid.
 - Select *General*.
 - Set Properties to very large values.
 - Select *OK* to continue defining the section.
 - Name the bent cap frame section.
 - Define the material as *55-0837S Core*.
 - Set the Mass Property Multiplier equal to 0.
 - Select *OK* to create the bent cap frame section.
- Create the bent column frame section.
 - Select *Section Designer* to define geometry and reinforcing.
 - Name the column section
 - Set the Base Material to be *55-0837S Cover*.
 - Designate the Design Type to be *Concrete Column* with *Reinforcement to be Checked*.
 - Select *Set Modifier*.
 - Change the *Mass* modifier to 0.
 - Select *OK* to save.
 - Select *Section Designer* to open the Section Designer Interface and create the *55-0837S Column* Section.
 - Create the section.
 - Set units to *kN, m, C*.
 - Select the *Draw* tab, then *Draw Caltrans Shape*, then *Draw Round* to create a default column cross-section.
 - Click anywhere on the grid to place the *Draw Round* object.
 - Select the *Arrow* icon in the left-hand toolbar and right-click on the object to edit its parameters.

The image shows the 'SD Section Data' dialog box. It has a title bar 'SD Section Data'. Inside, there's a 'Section Name' field with '55-0837S Column' and a 'Section Notes' field with a 'Modify/Show Notes...' button. Below is a 'Base Material' section with a '+' icon and a dropdown menu showing '55-0837S Cover'. The 'Design Type' section has three radio buttons: 'No Check/Design', 'General Steel Section', and 'Concrete Column' (which is selected). The 'Concrete Column Check/Design' section has two radio buttons: 'Reinforcement to be Checked' (selected) and 'Reinforcement to be Designed'. The 'Define/Edit/Show Section' section has a 'Section Designer...' button. The 'Section Properties' section has a 'Properties...' button. The 'Property Modifiers' section has a 'Set Modifiers...' button. At the bottom, there's a 'Display Color' checkbox and 'OK' and 'Cancel' buttons.

- Set parameters as defined in Table B.3 and select *OK* to save.
- Select *DONE* in the lower right-hand corner of Section Designer to save the bent column and return to the SD Section Data Window.
 - Select *Properties* to ensure the bent column cross-sectional properties match those defined in Table 4.2.
 - Select *OK* to create the bent column frame section.

Table B.3 Bent Column Section Designer Frame Properties

Geometry		
Height (m)	2.7432	
Width (m)	2.7432	
No. of Cores	1	
No. of Rings	2	
Rings		
Core	1	2
Cover (m)	0.0508	0.1206
No. of Bundles	57	
Bundle Type	Single	Single
Bundle Bar No.	#14	#14
Bundle Material	55-0837S Rebar	55-0837S Rebar
Conf. Type	Spiral	Spiral
Conf. Spacing (m)	1.8288	0.1016
Conf. Bar No.	#8	#8
Concrete Model		
Conf. Material	55-0837S Rebar	
Material	55-0837S Core	
Core Concrete	Core1	
Other Concrete	Mander-Unconfined	
Outer Concrete	Mander-Unconfined	

Caltrans Section Properties

Geometry

Shape: Round

Chamfer: 0.0625

Height: 2.7432

Width: 2.7432

☐ Small Base Dimensions

Base Height: 2.7432

Base Width: 2.7432

No. of Cores: 1

Casing

Thickness: 0

Longit. Factor: 0

Rings

No. of Rings: 2

Ring1 Cover: 0.0508

Ring2 Cover: 0.1206

Ring3 Cover:

Region	Ring	No. of Bundles	Bundle Type	Bundle Bar No.	Bundle Area	Bundle Material	Conf. Type	Conf. Spacing	Conf. Bar No.	Conf. Area	Conf. Material
Core1	Ring1	57	Single	#14	0.0015	0837S Rebar	Hoop	1.8288	#8	0.0005	0837S Rebar
Core1	Ring2	57	Single	#14	0.0015	0837S Rebar	Hoop	0.1016	#8	0.0005	0837S Rebar
Prestress		0	Tendon	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A
Casing		N/A	Casing	N/A	0	N/A	N/A	N/A	N/A	N/A	N/A

Concrete Model

Material: 55-0837S Core

Core Concrete: Core1

Other Concrete: Mander-Unconfined

Outer Concrete: Mander-Unconfined

OK

Cancel

DEFINING THE SUPERSTRUCTURE & SUBSTRUCTURE

- In order to create a bridge object, a deck cross-section is automatically applied to the layout line. In this model, the desired deck section is user-defined as a general frame section (55-0837S Deck). Therefore, the automatic deck cross-section needs to be created merely as a place holder to be later overwritten by the already defined deck frame section.
- Create a deck section by selecting *Deck Section* from the *Item* drop down window in the Superstructure section under the *Components* tab.
 - Select the *New* icon to begin creating a new deck section.
 - Select AASHTO-PCI-ASBI Standard.
 - Select *OK* without making any changes to the geometry because this deck section will later be overwritten and is therefore, trivial.
- Create foundation springs by selecting *Foundation Springs* from the *Item* drop down window in the Substructure section under the *Components* tab.
 - Select the *New* icon to begin creating a new foundation spring.
 - Name the foundation spring.
 - Ensure the units are kN, m, C
 - Click on the *Release Type* to select the fixity from the drop down window according to Table 4.4.
 - If partially fixed, specify the *Stiffness*.
 - Select *OK* to save.
 - Create both the Bent Foundation Spring and the Abutment Spring.

- Create each bent by selecting *Bents* from the *Item* drop down window in the Substructure section under the *Components* tab.
 - Select the *New* icon to begin creating a new bent.
 - Name the bridge bent.
 - Ensure the units are *kN, m, C*.
 - Specify Bent Data according to Table B.4.
 - Set Bent Type to *Single Bearing Line (Continuous Superstructure)* and Girder Support Condition to *Connect to Girder Bottom Only*.
 - Select *Modify/Show Column Data* to define bridge bent column properties.
 - Within the Bridge Bent Column Data window, modify properties according to Table B.4.
 - Select *OK* to save.
 - Select *OK* to save.
 - Create both Bent 2 and Bent 3.

Table B.4 Bridge Bent Properties
(kN, m, C)

Bridge Bent Data		
Bridge Bent Name	Bent 2	Bent 3
Cap Beam Length (m)	3.3528	3.3528
No. of Columns	1	1
Cap Beam Section	55-0837S Deck	55-0837S Deck
Bridge Bent Column Data		
Section	55-0837S Column	55-0837S Column
Distance (m)	1.6764	1.6764
Height (m)	10.7	11
Angle	0	0
Base Support	Bent Foundation Spring	Bent Foundation Spring
Moment Releases at Top of Column	All Fixed	All Fixed

- Create each abutment by selecting *Abutments* from the *Item* drop down window in the Substructure section under the *Components* tab.
 - Select the *New* icon to begin creating a new abutment. This abutment definition will be used for both Abutment 1 and Abutment 4.
 - Name the abutment.
 - Ensure the units are kN, m, C.
 - Set Girder Support Condition to *Connect to Girder Bottom Only* and Substructure Type to *Foundation Spring*.
 - Select *Abutment Spring* from the drop down window to define the Foundation Spring Property.
 - Select *OK* to save.

CREATING A BRIDGE OBJECT

- A bridge object assigns the superstructure and various substructure components to the layout line.
- Create a bridge object by selecting the *New* icon in the *Bridge Objects* section under the *Bridge* tab.
 - Name the bridge object.
 - Select 55-0837S as the Layout Line Name.
 - Define the Bridge Object Reference Line.
 - Add spans by entering the station location of the first bent in the Station (m) window.
 - Select *Add* (Span Label and Span Type will update automatically).
 - Bent 2 is located at 46.0139m
 - Bent 3 is located at 107.4442m
 - Select *OK* to create the bridge object.

- Assign abutments to the bridge object by selecting *Abutments* from the *Supports* drop down window in the Bridge Objects section under the *Bridge* tab.
 - Set Substructure Assignment to *Abutment Property* and select *Abutment 1&4* (the abutment substructure previously defined) from the drop down window.
 - Set Substructure Location Elevation to $-1.68m$ and Horizontal Offset to 0 .
 - Let Bearing Assignments remain set to the default *BBRG1* (a translationally fixed and rotationally free connection). Select the plus sign icon (+) to view the properties of this bearing link.
 - Set Elevation at Layout Line to $-1.68 m$ (equal with Substructure Location Elevation to create a zero length bearing) with Rotational Angle from Bridge Default set to 0 .
 - Assign these abutment settings to both the *Start Abutment* tab and *End Abutment* tab (above).
 - Select *OK* to assign.

- Assign bents to the bridge object by selecting *Bents* from the *Supports* drop down window in the Bridge Objects section under the *Bridge* tab.
 - To assign Bent 2, set Specify Bent Considered to be at the end of *Span1*.
 - In the Bent Assignment section, specify the Bent Property as *Bent 2* (the bent substructure previously defined) with *Default* Bent Direction, $-1.68 m$ Elevation, and 0 Horizontal Offset.
 - Let Bearing Assignments remain set to the default *BBRG1*.

- Set Elevation (At Layout Line) equal to -1.68 m with Rotational Angle from Bridge Default set to 0 .
 - To assign Bent 3, change the Specified Bent Considered to be at the end of *Span 2*. Change the Bent Property to *Bent 3*. All other properties are the same for both bent assignments.
 - Select *OK* to assign.
- Apply the bridge object assignments to the layout line by selecting the *Update* icon in the Update section under the *Bridge* tab.
 - Do NOT select the *Auto Update* icon. This will disable the user's ability to manually override any of the automated model settings which will be imperative in the steps to come.
 - Select the Bridge Object created and choose to *Update Linked Model*.
 - Specify the Discretization Information.
 - In the Structural Model Options section, select *Update as Spine Model Using Frame Objects*.
 - Select *OK* to update.
- To navigate the model, use the icons provided in the View section under the *Home* tab. To view the line model, select the icon with the check mark and uncheck *Extruded View*.

MANUALLY OVERRIDING AUTOMATED PARAMETERS

- For comparison purposes, this model of Bridge 55-0837S is designed to replicate the Finite Element model created in OpenSees. For the model to be best replicated, four default parameters need to be corrected:
 1. The deck section assigned in the bridge object needs to be overwritten with the general frame section created.
 2. Mass needs to be assigned at each joint.
 3. Local axes at the bents need to be altered.
- Overwrite the deck section assigned to the bridge object by selecting the entirety of the bridge deck nodes in the XY viewport.
 - Under the *Advanced* tab, select the *Frames* icon in the Assign section. Select *Frame Sections* from the drop down window.
 - Select *55-0837S Deck* (the deck frame section previously defined).
 - Select *OK* to apply the new frame section to the bridge deck.

- Manually apply the masses by selecting any given joint or group of joints in either the *XY* or *3D* viewport.
 - Under the *Advanced* tab, select the *Joints* icon in the Assign section. Select *Masses* from the drop down window.
 - The mass at each joint is applied As *Mass* along the *Joint Local* Coordinate System.
 - Assign mass values corresponding to each respective joint in Table B.5.
 - No rotational mass is added.
 - Ensure the Units are *kN, m, C*.
 - Select *OK* to apply the mass.

Table B.5 Masses assigned at each joint along the bridge deck and bent columns

Bridge Deck		
Joint Location	Joint No.	Local 1,2,3 Axis Direction (kN)
Abutment 1	1	40.9461
Along Span 1	2 - 10	81.8922
Bent 2	11	95.6095
Along Span 2	12 - 20	109.3268
Bent 3	21	95.5629
Along Span 3	22 - 30	81.7989
Abutment 4	31	40.8995
Bent Column 2		
Top	1	14.7025
Along Column	2 - 4	39.2067
Bottom	5	26.2447
Bent Column 3		
Top	1	15.1147
Along Column	2 - 4	40.3059
Bottom	5	26.6569

Joint Masses

Specify Joint Mass

☒ As Mass
☐ As Weight
☐ As Volume and Material Property

Material

Mass Direction

Coordinate System

Mass

Local 1 Axis Direction

Local 2 Axis Direction

Local 3 Axis Direction

Mass Moment of Inertia

Rotation About Local 1 Axis

Rotation About Local 2 Axis

Rotation About Local 3 Axis

Options

☐ Add to Existing Masses
☒ Replace Existing Masses
☐ Delete Existing Masses

Units

- View the local axes at each joint by selecting the check mark icon in the View section under the *Home* tab. Check *Local Axes* in the Joints section of the *Display Options for Active Window* window.

- Automatically, the abutment springs' local axes are oriented in line with the deck edge, -21° for Abutment 1 and $+25^\circ$ for Abutment 4 (see Figure 4.6). However, the bent foundation soil springs need to be aligned with Abutment 1 to be congruent with the OpenSees Bridge Model.

- Reorient the local axis at the bent bases according to Figure 4.6.
 - Select joint 21 (Bent 2) and joint 51 (Bent 3) in the XY viewport.
 - Under the *Advanced* tab, select the *Joints* icon in the Assign section. Select *Local Axes* from the drop down window.
 - Orient the selected axes according to Figure 4.6.
 - The u1, u2 and u3 DOFs are rotated by default. To keep the correct assignment of spring stiffness in the respective vertical, transverse and longitudinal directions, rotate the soil springs about the Global Y -90° and about the Global X -201° .
 - Select *OK* to apply.

- Overwrite the girder bearing to be ideally fixed so that the bent top node and corresponding deck node displace equally.
 - Select the automatically generated girder bearing link *BBRG1* from the drop down list in the Properties - Links window of the *Components* tab.
 - Click the *Modify* icon.
 - Click *Modify/Show for All...*

- Check all six Direction options in the Directional Control section of the Linear Link/Support Directional Properties window.
- Indicate that *Stiffness is Uncoupled*
- Set all directional stiffness to a high values. $1\text{E}+10$ N/m can be used.
- Click OK to save.
- Repeat for all links which are prefaced with the name BBRG1.

DEFINING THE RESPONSE SPECTRUM

- Define the design spectrum to be used in the fault-normal and fault-parallel response spectrum analysis.
 - Select *Response Spectrum* from the *Type* drop down window in the Functions section under the *Loads* tab.
 - Choose the Function Type *From File*.
 - Copy the values from Table B.6 into a .txt file with Periods running from 0 to 5sec with the corresponding P_s (g) in the adjacent column. Save this file.
 - Define the response function in the Response Spectrum Function Definition window.
 - Name the function.
 - Function Damping Ratio is 5%.
 - Select the .txt file using *Browse*.
 - Denote how many Header Lines to Skip.
 - Select *Display Graph*.
 - Select *Convert to User Defined* to imbed the values in the CSiBridge™ document, allowing the other .txt file to be moved or deleted.
 - Select *OK* to save.

**Table B.6 Caltrans SDC Design
Spectrum Data**

Period (sec)	Psa (g)	Period (sec)	Psa (g)	Period (sec)	Psa (g)
0.01	0.522686	0.15	0.892356	0.85	0.913194
0.02	0.531822	0.16	0.914375	0.9	0.893391
0.022	0.537514	0.17	0.934092	0.95	0.875195
0.025	0.545450	0.18	0.952711	1	0.857419
0.029	0.554750	0.19	0.969753	1.1	0.793836
0.03	0.557516	0.2	0.985467	1.2	0.737891
0.032	0.564002	0.22	1.007486	1.3	0.687659
0.035	0.573363	0.24	1.026236	1.4	0.642609
0.036	0.576447	0.25	1.034105	1.5	0.601370
0.04	0.588169	0.26	1.038831	1.6	0.562199
0.042	0.594519	0.28	1.048257	1.7	0.526867
0.044	0.600709	0.29	1.051087	1.8	0.495154
0.045	0.604071	0.3	1.053959	1.9	0.466718
0.046	0.607344	0.32	1.058716	2	0.441308
0.048	0.613574	0.34	1.061260	2.2	0.394913
0.05	0.619839	0.35	1.061657	2.4	0.356286
0.055	0.633146	0.36	1.061972	2.5	0.339213
0.06	0.646950	0.38	1.061045	2.6	0.323494
0.065	0.660695	0.4	1.059210	2.8	0.295351
0.067	0.666500	0.42	1.054312	3	0.271125
0.07	0.674891	0.44	1.048308	3.2	0.250019
0.075	0.689165	0.45	1.045620	3.4	0.231445
0.08	0.705275	0.46	1.042586	3.5	0.222997
0.085	0.721454	0.48	1.036122	3.6	0.215042
0.09	0.737416	0.5	1.030093	3.8	0.200380
0.095	0.753372	0.55	1.012006	4	0.187329
0.1	0.768957	0.6	0.996359	4.2	0.176113
0.11	0.799122	0.65	0.981859	4.4	0.165781
0.12	0.826969	0.66	0.976423	4.6	0.156388
0.13	0.851907	0.7	0.968423	4.8	0.147803
0.133	0.858486	0.75	0.955977	5	0.139894
0.14	0.873122	0.8	0.933755

CONDUCTING CALTRANS AUTOMATED FAULT CROSSING SEISMIC DESIGN

- The Caltrans Automated Fault Crossing Seismic Design function will run both the static analysis due to fault rupture ground displacement and response spectrum analysis due to ground shaking. These responses will be combined and represented as a demand on the bents in both the transverse and longitudinal directions (see Figure 5.8).
- Create a design request by selecting the *Design Request* icon in the Seismic Design section under the *Design/Rating* tab.
 - Select *Add New Request* to begin.
 - Name the design request.
 - Select the Bridge Object created.
 - Select *Caltrans Fault Crossing* as the Check Type.
 - Select a *Planar* Fault Definition and designate the fault crossing Station as *271.89 ft*. The station must be denoted in the units of feet, regardless of selected working units.
 - Set the Orientation to *Default* which orients the fault rupture perpendicular to the deck at the station it bisects.
 - Define the Parallel Fault Displacement by setting the ground Displacement for static analysis to be the *0.5 m* used in this study, and by setting the Response Spectrum Function to the user-defined *Caltrans SDC Spectrum* to define Fault Parallel ground motion.
 - To simultaneously consider the effects due to fault normal ground motion, set the Normal Uniform Acceleration R.S. Function to the user-defined *Caltrans SDC Spectrum*, as well.
 - Select OK to create.

- Run Caltrans Automated Fault Crossing Seismic Design Request by selecting the *Run Seismic* icon in the Seismic Design section under the *Design/Rating* tab.
 - Set the fault crossing design request Action to *Design*.
 - Select *Design Now* to run analyses.
- The Bridge Seismic Design 01 – Bent D-C window will appear when the analysis is complete. Select Done, for now. This window will be discussed further in the Interpreting Results portion of this tutorial.

Bridge Seismic Design 01 - Bent D-C

File View Format-Filter-Sort Select Options

Units: As Noted Bridge Seismic Design 01 - Bent D-C

DesReqName	BridgeObj	DCategory	SpanName	Station	Direction	GenDispl	Demand	Cap
Seismic Fault	BO 55-08375	D	Span1	46.01392	TRANS	TR1_Seismic Fault Ru	0.163358	0.2
smic Fault Ruptl	BO 55-08375	D	Span1	46.01392	LONG	LG1_Seismic Fault Ru	0.031865	0.1
smic Fault Ruptl	BO 55-08375	D	Span2	107.44416	TRANS	TR2_Seismic Fault Ru	0.188306	0.2
smic Fault Ruptl	BO 55-08375	D	Span2	107.44416	LONG	LG2_Seismic Fault Ru	0.026739	0.1

INTERPRETING RESULTS

- View the bridge displacement due to each component of fault rupture analysis by selecting the triangle icon in the Display section under the *Home* tab.
 - Select the desired response component to view in the dropdown window. Each case refers to a deformed bridge shape due to the following loads:
 - Gravity Load (GRAV)
 - Ritz Vectors (MODAL)
 - Fault Parallel Response Spectrum (RS_DIS)
 - Fault Normal Response Spectrum (RS_UNIF)
 - Fault Rupture Displacement (DIS)
 - Push Over Analysis in the respective transverse and longitudinal directions about Bent 1 (PO_TR1 and PO_LG1)
 - Push Over Analysis in the respective transverse and longitudinal directions about Bent 1 (PO_TR2 and PO_LG2)
 - Select *OK* to view.

- Results from all load cases can be output by selecting *Tables* in the Display section under the *Home* tab.
 - The displacement due to all load cases at the top and bottom joints of each bent can be output by checking Displacements under Joint Output in Analysis Results.
 - The displacements at the abutments measure by the change in length in the attached abutment soil springs can be output by checking Link Output under Element Output in Analysis Results.
 - The bent demand (drift) generated by the Caltrans Automated Fault Crossing Seismic Design is output by checking Bridge in Design Data.
 - These bent drifts are calculated by combining the responses due to only quasi-static analysis from fault rupture offset and the fault-parallel response spectrum analysis.
 - Bent drift due to rotation at the top and bottom ends of the bents are also excluded in the demand calculation, i.e., the equation used by CSiBridge™ to calculate bent drift is $U_t - U_b - L(R_t + R_b)$ where U and R respectively represent the translational and rotational displacement at the top node(t) and bottom node (b) of a given bent with length, L.
 - Bent drift quantities were not used in the validation of Caltrans Automated Fault Crossing Seismic Design because the lumped plasticity and distributed plasticity models adopted by CSiBridge™ and OpenSees, respectively, provide different values of angle of rotation at the ends of the members.

APPENDIX C: REVIEW OF RITZ VECTOR THEORY

The Rayleigh-Ritz method is a general technique for reducing the number of DOF's of a complex structure and finding approximations to its lower natural frequencies and modes (Chopra, 2012). This method assumes displaced shape vectors called Ritz vectors for use in the eigenvalue problem which discretizes the number of DOF's and simplifies the computational effort in approximating the natural frequencies. The success of the Rayleigh-Ritz method depends on how well linear combinations of Ritz vectors can approximate the natural modes of vibration. The Ritz vectors can, therefore, be approximated in one of two ways; either by physical insight into natural mode shapes expected of a given type of structure derived from story stiffness and mass distribution as seen in Figure C.1 or by mapping the static displacement the structure undergoes due to a spatial distribution of external forces $\mathbf{p}(t)$. The use of the later method for determining approximate is considered Force-Dependent Ritz vectors where the equation of motion for a system of n degrees of freedom is subjected to external dynamic forces, $\mathbf{p}(t)$, where a spatial distribution of forces defined by the vector, $\mathbf{s}$, does not vary with time, and the time dependence of all forces is given by the same scalar function $p(t)$ as represented in Eq. C.1.

$$\mathbf{p}(t) = \mathbf{s}p(t) \quad (C.1)$$

To determine the Force-Dependent Ritz vectors, first determine the first Ritz vector, ψ_1 , by solving for the displacement of the structure, y_1 , due to an applied force, $\mathbf{s}$, in Eq C.2, and then normalizing y_1 using Eq C.3.

$$\mathbf{s} = k\mathbf{y}_1 \quad (C.2)$$

$$\psi_1 = \frac{y_1}{(y_1^T m y_1)^{\frac{1}{2}}} \quad (C.3)$$

Determine additional Ritz vectors, ψ_n , by solving y_n in Eq C.4 and then orthogonalizing y_n with respect to previous vectors $\psi_1, \psi_2, \dots, \psi_{n-1}$ by repeated solving of Eq C.5 through Eq. C.7 for $i = 1, 2, \dots, n-1$. Finally, solve for a given Ritz vector, ψ_n , by normalizing the “pure” vector, $\hat{\psi}_n$, using Eq. C.7.

$$k y_n = m - \psi_{n-1} \quad (C.4)$$

$$a_{in} = \psi_i^T m y_n \quad (C.5)$$

$$\hat{\psi}_n = y_n - a_{in} \psi_i \quad (C.6)$$

$$\psi_n = \frac{\hat{\psi}_n}{(\hat{\psi}_n^T m \hat{\psi}_n)^{\frac{1}{2}}} \quad (C.7)$$

Figure C. 1 - Ritz vectors for a five-story frame (Chopra, 2012)

APPENDIX D: RESULT COMPARISON QUANTITIES

Table D.1 - Bridge 55-0837S: Abutment Displacement (m)

Abut	Program	QS		RSA-FP		RSA-FN		Combined	
		Trans	Long	Trans	Long	Trans	Long	Trans	Long
1	OpenSees	-0.1382	-0.0128	0.2018	0.0606	0.0643	0.1370	0.4043	0.2104
	CSiBridge™	0.1307	-0.0352	0.1882	0.0572	0.0787	0.1701	0.3976	0.2625
4	OpenSees	0.1393	-0.0120	0.1931	0.0676	0.0675	0.1321	0.3999	0.2117
	CSiBridge™	0.1170	0.0031	0.1838	0.0567	0.0775	0.1644	0.3784	0.2242

Table D.2 - Bridge 55-0837S: Bent Top Node Displacement (m)

Bent	Program	QS		RSA-FP		RSA-FN		Combined	
		Trans	Long	Trans	Long	Trans	Long	Trans	Long
2	OpenSees	-0.2986	0.1460	0.0791	0.0480	0.0517	0.1312	0.4294	0.3252
	CSiBridge™	-0.2969	0.1551	0.0769	0.0468	0.0458	0.1599	0.4196	0.3617
3	OpenSees	0.3179	-0.0920	0.0809	0.0193	0.0491	0.1317	0.4479	0.2430
	CSiBridge™	0.2966	-0.0980	0.0731	0.0450	0.0838	0.1407	0.4534	0.2838

Table D.3 - Bridge 55-0837S: Bent Bottom Node Displacement (m)

Bent	Program	QS		RSA-FP		RSA-FN		Combined	
		Trans	Long	Trans	Long	Trans	Long	Trans	Long
2	OpenSees	-0.4171	-0.1675	0.0273	0.0251	0.0254	0.0814	0.4698	0.2740
	CSiBridge™	0.4028	0.1908	0.0274	0.0207	0.0232	0.0861	0.4534	0.2976
3	OpenSees	0.4229	-0.1522	0.0318	0.0066	0.0343	0.0746	0.4890	0.2334
	CSiBridge™	-0.4097	-0.1774	0.0264	0.0174	0.0437	0.0731	0.4798	0.2679

Table D.4 - Bridge 55-0939G Fault A: Abutment Displacement (m)

Abut	Program	QS		RSA-FP		RSA-FN		Combined	
		Trans	Long	Trans	Long	Trans	Long	Trans	Long
1	OpenSees	-0.1810	-0.0750	0.1963	0.0100	0.0231	0.0438	0.4004	0.1288
	CSiBridge™	0.0867	-0.0922	0.1692	0.0247	0.0348	0.0734	0.2908	0.1903
5	OpenSees	0.0420	-0.0342	0.0625	0.0254	0.0104	0.0428	0.1149	0.1024
	CSiBridge™	0.0001	0.0049	0.0313	0.0221	0.0103	0.0734	0.0417	0.1004

Table D.5 - Bridge 55-0939G Fault A: Bent Top Displacement (m)

Bent	Program	QS		RSA-FP		RSA-FN		Combined	
		Trans	Long	Trans	Long	Trans	Long	Trans	Long
2	OpenSees	-0.3413	-0.0413	0.0585	0.0244	0.0074	0.0422	0.4072	0.1079
	CSiBridge™	-0.2672	-0.0372	0.0856	0.0180	0.0160	0.0583	0.3688	0.1135
3	OpenSees	0.3064	-0.0211	0.0721	0.0127	0.0090	0.0409	0.3875	0.0747
	CSiBridge™	0.3836	0.0089	0.0578	0.0124	0.0112	0.0548	0.4526	0.0761
4	OpenSees	0.4900	0.0204	0.0916	0.0063	0.0119	0.0392	0.5935	0.0659
	CSiBridge™	0.5049	0.0026	0.0570	0.0076	0.0139	0.0504	0.5758	0.0606

Table D.6 - Bridge 55-0939G Fault B: Abutment Displacement (m)

Abut	Program	QS		RSA-FP		RSA-FN		Combined	
		Trans	Long	Trans	Long	Trans	Long	Trans	Long
1	OpenSees	0.0625	0.0272	0.2171	0.0558	0.0231	0.0438	0.3027	0.1268
	CSiBridge™	0.0134	0.0305	0.1317	0.0414	0.0348	0.0734	0.1799	0.1453
5	OpenSees	0.1505	0.1030	0.0510	0.0218	0.0104	0.0428	0.2119	0.1676
	CSiBridge™	-0.0766	-0.0541	0.0458	0.0225	0.0103	0.0734	0.1327	0.1500

Table D.7 - Bridge 55-0939G Fault B: Bent Top Displacement (m)

Bent	Program	QS		RSA-FP		RSA-FN		Combined	
		Trans	Long	Trans	Long	Trans	Long	Trans	Long
2	OpenSees	-0.5357	0.0058	0.1529	0.0135	0.0074	0.0422	0.6960	0.0615
	CSiBridge™	-0.5061	0.0269	0.1009	0.0144	0.0160	0.0583	0.6230	0.0996
3	OpenSees	-0.4023	-0.0108	0.1056	0.0082	0.0090	0.0409	0.5169	0.0599
	CSiBridge™	-0.3523	0.0335	0.0859	0.0097	0.0112	0.0548	0.4494	0.0980
4	OpenSees	0.3625	-0.0138	0.0603	0.0082	0.0119	0.0392	0.4347	0.0612
	CSiBridge™	0.4376	-0.028	0.0509	0.007	0.0139	0.0504	0.5024	0.0854