20-8 ANALYSIS OF ORDINARY BRIDGES THAT CROSS FAULTS

Introduction

A bridge that crosses an active fault is subject to a severe combination of seismic hazards. The ground shaking component can cause a large dynamic deformation demand due to near fault effects such as directivity and the velocity pulse. The surface rupture component can cause an additional large quasi-static deformation demand due to the fault offset and angle of rupture relative to the bridge. While a nonlinear time history analysis (NLTH) using multiple time history records may be used to estimate the seismic demands for bridges crossing faults, more simplified methods may be appropriate for ordinary bridges. That being the case, an alternative method is presented here with simplified procedures appropriate for bridge designers addressing typical strike-slip fault crossings, the most common faulting situation in California. The analysis presented in this document combines these seismic hazards in a simplified approach. This simplified procedure may be used for ordinary bridge fault crossing projects in lieu of a nonlinear time history analysis.

Many faults have small offsets and the resulting deformation can be addressed using ductile columns with adequate displacement capacity and supports with adequate seat length. For larger fault offsets, hinges and isolation bearings can be designed to handle the resulting displacements. For very large offsets other strategies, such as designing the bridge with wide bents that can slide under the superstructure while continuing to support it, may be needed. Addressing fault offsets is more complex for existing bridges.

General Purpose and Problem Statement

Although a few exceptions exist, the fault rupture hazard is addressed only for Holocene (< 10,000 years) faults identified by the California Geologic Survey in Alquist-Priolo Earthquake Fault Zone maps. According to Petersen et al (2011), "... fault rupture hazard analysis should be an important consideration in the design of structures or lifelines that are located near the principal fault, within about 100m (330ft) of well-mapped active faults with a simple trace, and within 300m (1000ft) of faults with poorly defined or complex traces." When a bridge crosses such a fault, it must be designed for the displacement demand resulting from a static fault offset, the dynamic response due to ground shaking, and any other fault-induced hazards (e.g., creep) that may occur at the site. The larger of the average deterministically-derived and the probabilistically-derived (with 5% in 50 years probability of exceedance) predicted fault offset, or a site-specific predicted offset obtained from a field investigation should be used. All recommendations should include an evaluation of the probability of rupture occurring off mapped fault traces and incorporate any available site-specific data(see Petersen et al). When the deterministically derived predicted fault offset is much larger than the probabilistically derived predicted fault offset, a risk assessment study is recommended to justify the potentially large cost. In such cases the engineer can ask the Office of Earthquake Engineering Analysis and Research (OEEAR) or the Structures Design Oversight Representative (SDOR) for a reassessment of the predicted offset as described in MTD 20-11.

Surface faults can vary from a well-defined single trace to a poorly-defined zone of disruption and from a horizontal to a nearly vertical ground displacement (See Figure 1). The location of the fault (or fault zone) with respect to the structure and a determination of the design fault offset shall be included in the Seismic Recommendations of the project's Foundation Report. The bridge engineer uses this information to meet the performance requirements in Caltrans' Seismic Design Criteria (SDC).

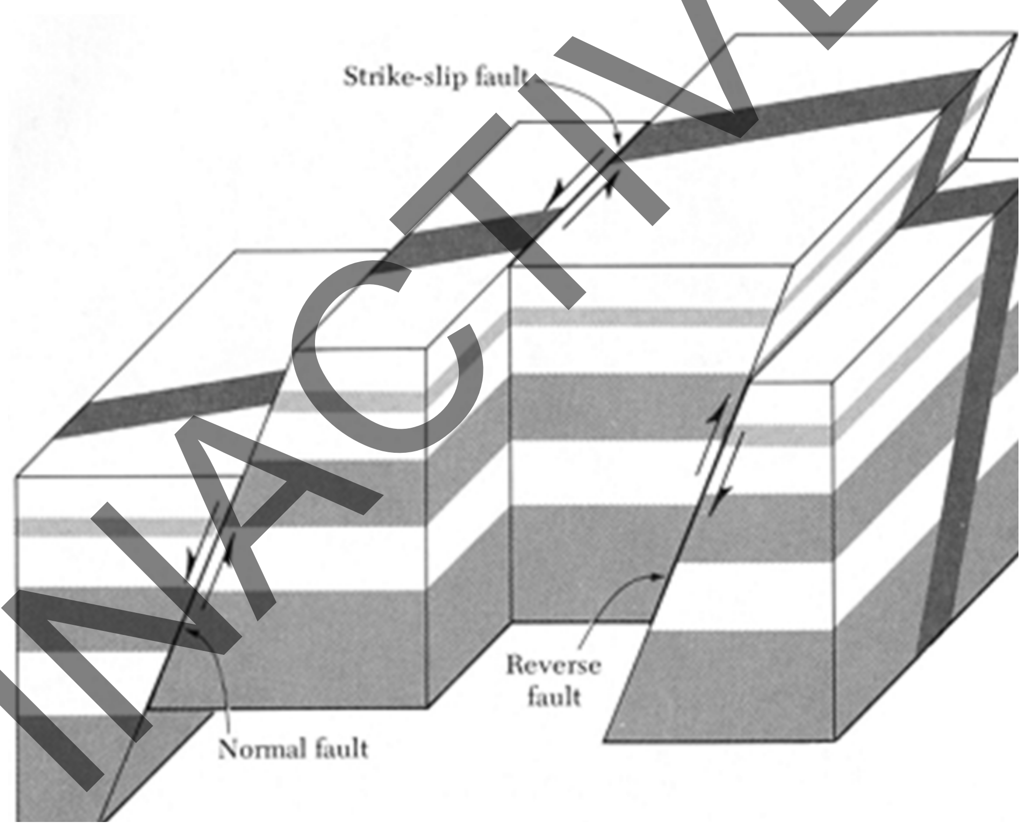

Figure 1. Schematic of main types of faults.

Procedure

A simplified method is provided for designing Ordinary Standard and Ordinary Non-Standard bridges that cross faults, based on research conducted by Professor Anil K. Chopra at the University of California at Berkeley.

The abutment and bridge foundations on one side of a strike–slip fault are offset an equal and opposite distance from the bridge foundations on the other side of the fault (See Figure 2). In addition, the bridge is subjected to ground motion. The resulting static and dynamic displacements are combined to obtain the seismic demands. The response of interest is the relative displacement between the top and bottom of the columns and between the superstructure and the abutment seats. Other responses, such as shear and flexural demands, will be based on plastic hinging of the columns.

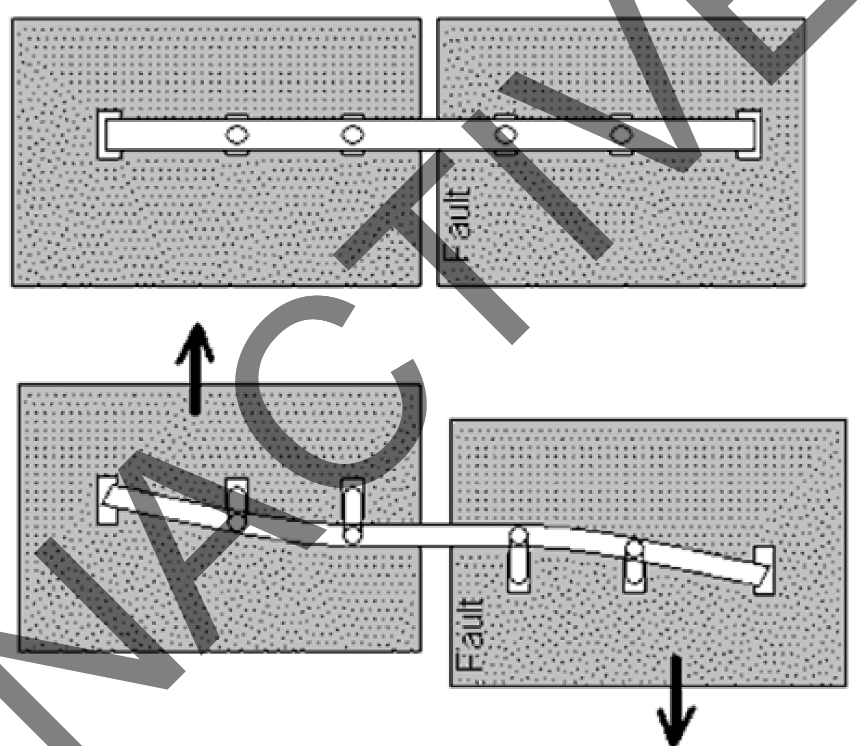

Figure 2. Drawing of a bridge crossing a right-lateral strike-slip fault that is perpendicular to the bridge. Note that in this example the abutment shear keys did not break and that the bents closest to the fault have the most relative column displacement.

Strike-slip fault crossings should be analyzed and designed for one of the following situations:

> When the fault is within 30 degrees of being normal to the bridge, analyze and design the bridge for the vector component of the fault offset normal to the bridge and for ground shaking using the linear Dynamic Method (see next section).

When the fault is at other angles to the bridge, analyze and design the bridge for the fault offset and for ground shaking using the Linear Static Method (see next section).

When a bridge crosses several fault traces, crosses a dipping fault or a fault characterized primarily by slip-slip movement, or is subject to other fault impacts such as creep, the engineer should consult with OEEAR or with the SDOR for guidance.

Steps of Procedure

1: Obtain the Design Fault Offset and Ground Shaking Hazard for the Bridge Site

The predicted location, amount, and direction of displacement at the structure due to the fault offset is provided by Geotechnical Services (GS) or by a geotechnical consultant with GS approval. The displacement of the longitudinal and/or the transverse vector component of the predicted fault offset (called the Design Fault Offset) is based on the larger of the probabilistic or deterministic offset or a site-specific offset as described on page 1 of this document. The Ground Shaking Hazard (either The Peak Ground Acceleration [PGA] or the Design Spectrum) is also provided, as described in Caltrans SDC Appendix B.

2: Obtain the Quasi-Static Response of the Structure due to the Design Fault Offset

A model of the bridge, including column plastic hinges (and possibly nonlinear springs for the shear keys and soil at the abutments based on the parameters provided in the SDC) is required to capture the behavior of the bridge for the Design Fault Offset. Gravity loads are applied to the bridge model followed by foundation offsets due to the fault movement. The relative displacement between the top and bottom of the columns (and between the superstructure and abutment seats) are recorded as the fault offset displacements.

3: Obtain the Dynamic Response of the Structure

The UC Berkeley Fault Rupture Study proposed three alternate procedures for computing the dynamic part of the response: (1) Modal Pushover Analysis (MPA), (2) Linear Dynamic Analysis (LDA), and (3) Linear Static Analysis (LSA). MPA is the most complicated procedure and requires special purpose software to make it convenient for use in design. LDA is less difficult and the results can be conveniently obtained using SAP2000 software. LSA is the easiest to use but it may be too conservative since it excites the structure with 2.5 times the peak ground acceleration (see below). Therefore, LDA should be used whenever possible. It is not recommended that MPA be used at this time due to a lack of adequate software.

A. Linear Static Analysis (LSA)

The dynamic response of the nonlinear bridge can be estimated with a linear analysis.

Furthermore, the elastic response of the bridge can be conservatively estimated by a static analysis of the structure due to the lateral forces = m·$i_{eff}\,A_{\max}$, where,
m = Structural mass matrix (mass of superstructure at the bents and abutments)
i_{eff}= Fault rupture influence vector (normalized displacements due to unit offset)
$A_{\max}$= Peak response spectrum acceleration.

Because $A_{\max} \approx 2.5 \cdot PGA$, the lateral force (F) at the top of the substructure is computed as:

$$F = 2.5 \cdot mass \cdot PGA \cdot i_{eff}$$

B. Linear Dynamic Analysis (LDA)[1]

LDA is usually carried out using a single-mode analysis of the most dominant mode of the bridge for fault rupture. Note that the most dominant mode for fault rupture may be different from the most dominant mode in a non-fault rupture situation.
The peak dynamic response is computed as follows:

1. Compute the vibration periods (T_n) and mode shapes (ϕ_n) of the bridge.

2. Compute the effective influence vector (i_{eff}).

3. Identify the most dominant mode by static analysis of the bridge using the following procedure[2]:

   a. Compute the displacement r^{st} by static analysis of the bridge due to forces equal to ($m \cdot i_{eff}$) applied at the structural degrees of freedom(DOFs).

   b. Compute the modal static response, r_n^{st}, by static analysis of the bridge due to forces ($\Gamma_n m\phi_n$) applied at the structure DOF, where
   $\Gamma_n = \phi_n^T m i_{eff} \big/ \phi_n^T m \phi_n$

   c. Compute the modal contribution factor for the nth mode, $\overline{r}_n = r_n^{st} \big/ r^{st}$

   d. The most dominant mode is the mode with the largest modal contribution factors.

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[1] The LDA procedure assumes that only a single mode dominates the response. In some cases, it may be necessary to consider several modes. Always check the first ten or so modes to ensure only a single mode has the same shape as the offset structure and most of the participating mass.

[2] Step 3B provides a way of identifying the most dominant mode for a given structure. For simple structures, the most dominant mode is easily identifiable by an inspection of the various mode shapes. For instance, when the bridge is normal to the fault, the deformed shape under fault rupture displacement involves movement of the supports on one side of the fault in the opposite direction of the supports on the other side of the fault. These deformations cause the superstructure deck to rotate in plane around a point on the fault line. The most dominant mode for fault rupture has to be a mode that involves a similar deformed shape.

4. Compute the displacement r_0 by linear analysis of the bridge due to equivalent static forces, $s_n = \Gamma_n m \phi_n A_n$, where s_n corresponds to the most dominant mode and A_n is the spectral acceleration corresponding to T_n, the period of the most dominant mode.

4: Combine the Static and Dynamic Response to Obtain the Seismic Demand

The peak values of seismic demands are obtained by superposition of the peak values of the static fault rupture and dynamic ground shaking parts of the response to provide a generally conservative estimate of deck displacement and column drifts, when compared to the results of the "Exact" analysis.

5: Perform a Pushover Analysis at Each Bent to Obtain the Seismic Capacity

A pushover analysis at each bent is performed to ensure that the displacement capacity is greater than the displacement demand obtained in Step 4. The displacement capacity is reached when degradation threatens the stability of the structure or when is there's a 20% drop in the load-carrying capacity of the bent (see SDC Section 4). An example of a pushover analysis is presented in the fault crossing design example in Bridge Design Aids Section 14-6. The bent should be pushed in the same direction as the Design Fault Offset.

Conclusion

A method for obtaining the displacements at columns and abutments at fault crossings has been presented. All the requirements in the SDC must also be followed. Adequate bearing seats must be provided so the superstructure can slide at the abutment, bent, or hinge seats without falling. Abutment shear keys are ignored since they are designed to fail during a large earthquake.
If the shear keys don't break they will need to be addressed as they can cause large column displacements by restraining the ends of the superstructure. When the end of the superstructure cannot move freely it should be modeled as fixed or with springs.

References

1. Caltrans, "*Seismic Design Criteria*"
2. Chopra Anil K., and Rakesh K. Goel, "*Analysis of Ordinary Bridges Crossing Fault Rupture Zones*," Research Conducted for the California Department of Transportation Contract No. 59A0435, Earthquake Engineering Research Center, University of California at Berkeley, February 2008, *Report No. UCB/EERC-2008/01*. (http://www.dot.ca.gov/hq/esc/earthquake_engineering/stap/).
3. Caltrans "*Bridge Design Aids*" Section 14 Seismic".
4. Petersen, M. and others, 2011. "Fault displacement hazard for strike-slip fault," Bulletin of the Seismological Society of America.

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