20-17 Understanding Directionality Concepts in Seismic Analysis

Introduction

There are several sources of uncertainty when determining the direction of the ground motion for the seismic analysis of bridges. Bridge designers often don't know in which direction the largest ground motion will occur at a bridge site. There can also be uncertainty about which direction of ground motion creates the maximum demands on bridge members. This memo addresses 'Directionality' for each of the seismic analysis methods permitted in the Caltrans Seismic Design Criteria (SDC).

In 1943 Caltrans began requiring that the horizontal earthquake force must be applied at the center of mass of a bridge in enough directions to obtain the maximum demand on each member. In 1975 Caltrans introduced the 30% rule for combining the longitudinal and transverse seismic demands to obtain the maximum demand on bridge members. In 1998, the CQC3 Method[1] was proposed (Menun and Der Kiureghian, 1998) for obtaining the maximum demands on bridge members. All of these procedures were meant to address directionality. However, the CQC3 method was found to give the most realistic results when a bridge is analyzed using the Elastic Dynamic Analysis (EDA) method. This memo provides guidance criteria to account for directionality when the EDA or other seismic analysis methods are used.

Seismic Analysis Methods

The engineer must choose the best seismic analysis method (based on the complexity of the bridge) in order to obtain the best estimate of the seismic displacement demands. For instance, it is difficult to determine the seismic demands on an unbalanced structure using the Equivalent Static Analysis (ESA) method. Moreover, obtaining the demands on a structure with pronounced nonlinear behavior may be difficult using the EDA method. This section describes how to address directionality using the three most common analytical methods for obtaining seismic demands.

1. The Complete Quadratic Combination 3 (CQC3) Method is briefly described in this memo. Readers wishing more information on CQC3 and the other combination rules should consult the 'References' or a structural dynamics textbook.

Nonlinear Time History Analysis (NLTHA) Method

The AASHTO Seismic Guide Specifications (AASHTO, 2011) require that at least seven sets of independent time histories of ground motion shall be applied in orthogonal directions at the bridge supports. The peak response of bridge members for each set of time histories shall be recorded. Uncertainty as to the direction of the ground motion that will produce the peak response for bridge members is addressed by orienting the time histories at different angles (see Figure 20-17.1 below). When the same time history is applied in two horizontal directions, then three orientations are required (0, 30, and 60 degrees). When different time histories are applied, then four orientations are required (0, 30, 60, and 90 degrees). For each orientation (and for each of the seven sets of time histories) the peak response at each pertinent Degree of Freedom (DOF) is recorded. This will be (3 orientations) x (7 sets of times histories) = 21 peak responses at each pertinent DOF when the same time history is applied in two orthogonal directions. It will be (4 orientations) x (7 sets of time histories) = 28 peak responses when different time histories are applied in each orthogonal direction. The bridge is designed for the average of the recorded peak responses at each degree of freedom of interest. If fewer than seven sets of time histories are used then the maximum rather than the average response shall be used for design.

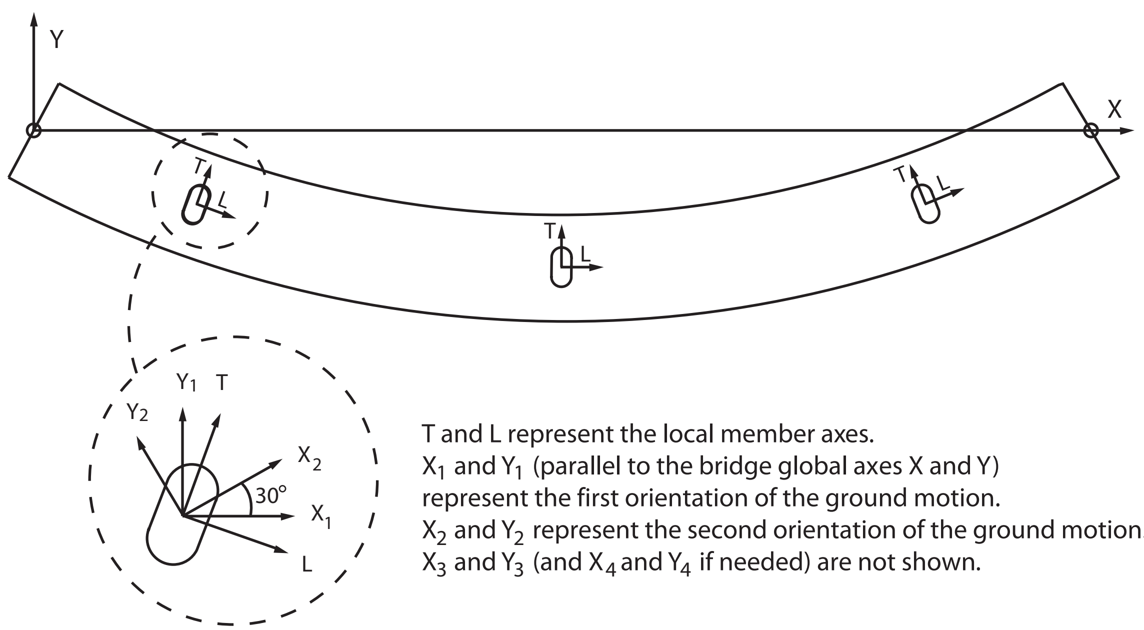


Figure 20-17.1 Orientation of Ground Motion for Nonlinear Time History Analysis.

Elastic Dynamic Analysis (EDA) Method using Multimodal Spectral Analysis

Definitions

Design Spectrum (Acceleration Response Spectrum): Defines the hazard at the site. It has a random orientation and it is equally probable in all directions.

Combination Rule 1 (30% Rule): Subjects the bridge to two equal orthogonal (based on the engineer's choice of a coordinate system) design spectra and combines 100% of the response in one orthogonal direction with 30% of the response in the other direction, and vice versa using absolute values of the displacements (see Figure 20-17.3 and Figure 20-17.5). The maximum of the two cases is used as the displacement in the transverse and longitudinal direction at the top of the columns and at other components for design. This method will be replaced by Combination Rule 2 (CQC3).

Combination Rule 2 (CQC3): Analyze the bridge for two equal orthogonal (based on the engineer's choice of a coordinate system) design spectra. Then the motion is rotated in angular increments to produce an envelope of maximum effects. CQC3 implements this combination rule mathematically and the results are compiled internally to produce the maximum demands (see Figure 20-17.4). The CQC3 has been shown to produce a more stable and realistic result for the top-node column displacements and the resulting demands are less affected by the orientation of the input ground motion. This method will be replaced by the Square Root Sum of Squares (SRSS) Method (see Example Problem).

Caltrans' Office of Earthquake Engineering (OEE) recently completed a study of straight, skewed, and curved six span bridges on two column and single oblong column bents (see Figure 20-17.2). These bridges were subjected to a single direction and to two orthogonal directions of ground motion. The goal was to see what effect the different directionality rules had on the maximum top-of-column local axis displacement demands.

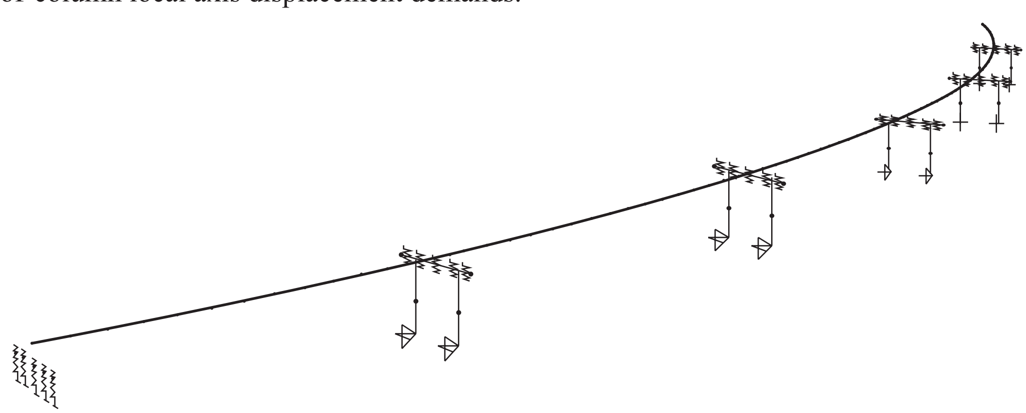


Figure 20-17.2 One of the Bridges Considered in the OEE Study.

The results of the study showed little difference in the maximum displacement for the different cases. However, the CQC3 method was found to envelope results from the 30% and other combination rules that were studied. Moreover, it is the most realistic method for obtaining the maximum displacement demands along the local axes of each member. This method has been automated in structural analysis software such as CSI Bridge where the resultant displacement output in the local member axes is provided[2]. On the basis of this study, Caltrans has adopted the CQC3 combination when performing EDA.

In the EDA Method, the normalized modal displacements at each DOF are multiplied by participation factors and spectral responses. The products are summed together using either the Complete Quadratic Combination (CQC) or the Square Root of the Sum of the Squares (SRSS) to obtain the response at each DOF. Then CQC3 is used to find the direction that produces the maximum demand. This method is described in several textbooks (Wilson, 2004). CQC3 is the preferred procedure for obtaining displacement estimates for both curved and straight bridges. If CQC3 is not available (for instance, for engineers who do not have CSI Bridge) then SRSS may be used in Combination Rule 2 in the interim to account for uncertainty in the direction of the ground motion.

Generally, realistic results are obtained if the analysis tool is capable of producing displacement results along the principal axes of each column (L and T shown in Figure 20-17.5 and Figure 20-17.6 represent the longitudinal and transverse directions for each column). If L and T are not directly available from the analysis tool then global X and Y directions can be used and the resulting displacements transformed to L and T for design purposes using the equations in Figure 20-17.6. Studies have shown the transformed displacements L and T (from X and Y) are larger, and unnecessarily conservative compared to the actual L and T displacements.

Figure 20-17.5 shows a sketch of a curved bridge for using Combination Rule 1. In the equations $X_{y\text{-direq}}$ is the displacement in the X direction due to ground shaking in the Y direction (due to twisting or other complicated behavior) and $X_{x\text{-direq}}$ is the displacement in the X direction due to ground shaking in the X direction. Similarly, $Y_{x\text{-direq}}$ is the displacement in the Y direction due to ground shaking in the X direction and $Y_{y\text{-direq}}$ is the displacement in the Y direction due to ground shaking in the Y direction. Figure 20-17.6 shows a sketch of how the global responses could be rotated into the local system if the FEM software isn't able to define the local axes.

2. The local displacements are labeled u1, u2, and u3 (and shown as red, green, and blue arrows on the bridge model).

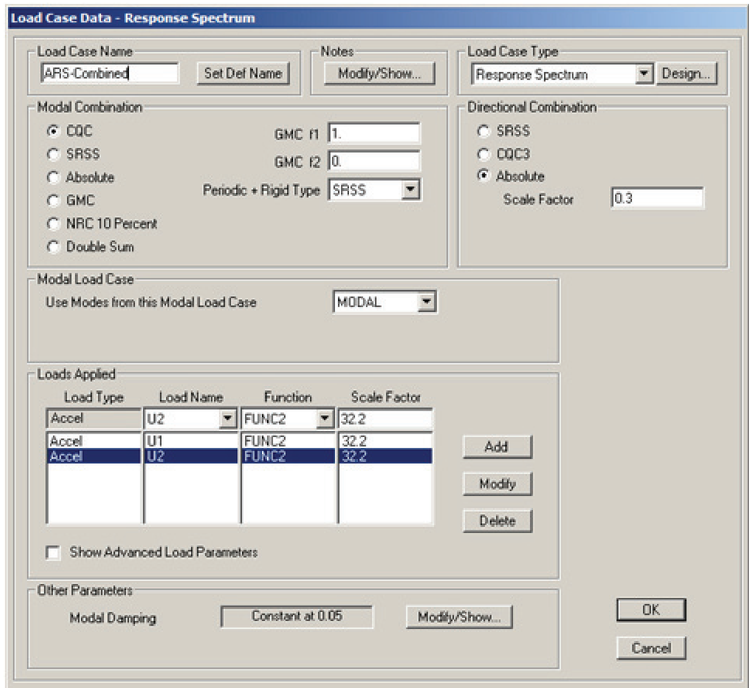


Figure 20-17.3 Old Combination Rule 1 in CSI Bridge

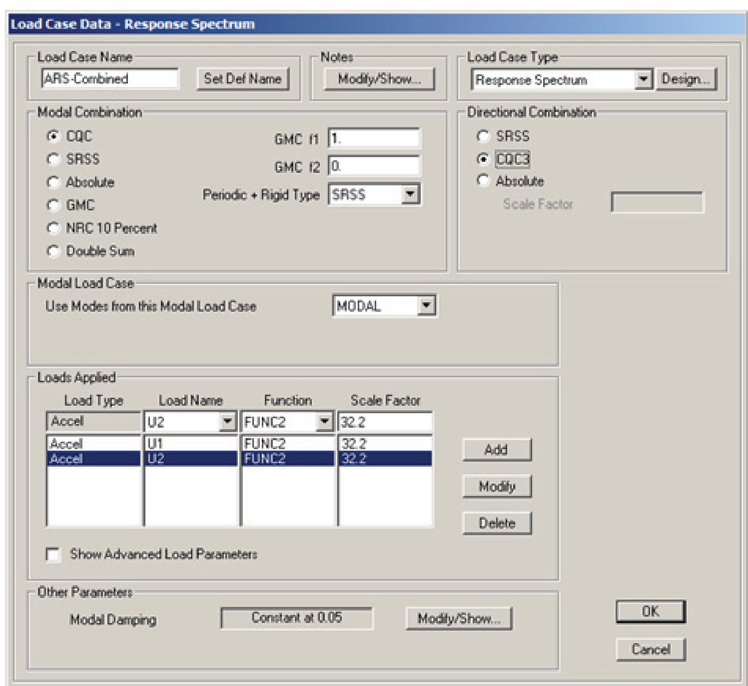
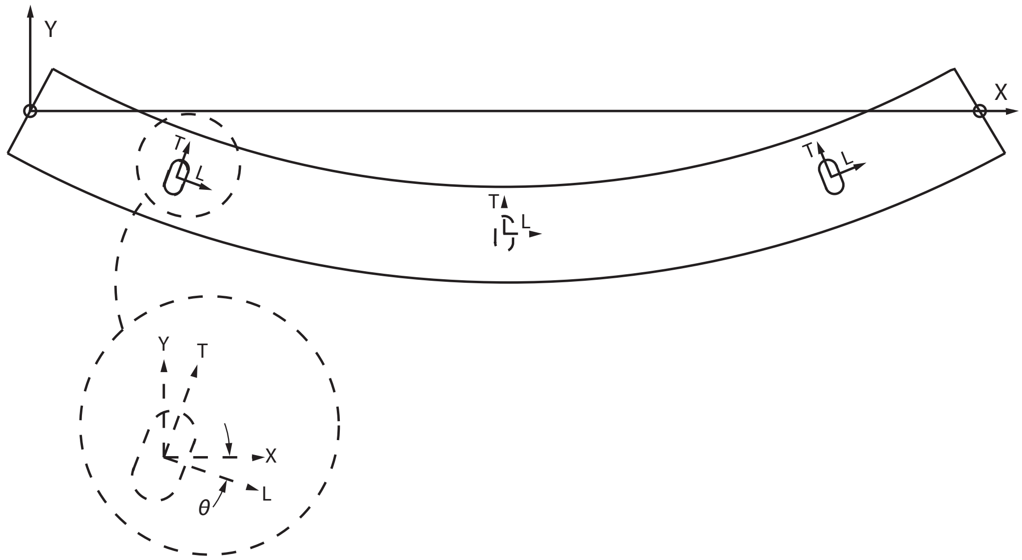


Figure 20-17.4 Old Combination Rule 2 in CSI Bridge.



$$L = \max \begin{cases} (X_{y\text{-}direq} + 0.3\, X_{x\text{-}direq})\, abs\,(\cos\theta) + (Y_{y\text{-}direq} + 0.3\, Y_{x\text{-}direq})\, abs\,(\sin\theta) \\ (X_{x\text{-}direq} + 0.3\, X_{y\text{-}direq})\, abs\,(\cos\theta) + (Y_{x\text{-}direq} + 0.3\, Y_{y\text{-}direq})\, abs\,(\sin\theta) \end{cases}$$

$$T = \max \begin{cases} (X_{y\text{-}direq} + 0.3\, X_{x\text{-}direq})\, abs\,(\sin\theta) + (Y_{y\text{-}direq} + 0.3\, Y_{x\text{-}direq})\, abs\,(\cos\theta) \\ (X_{x\text{-}direq} + 0.3\, X_{y\text{-}direq})\, abs\,(\sin\theta) + (Y_{x\text{-}direq} + 0.3\, Y_{y\text{-}direq})\, abs\,(\cos\theta) \end{cases}$$

Figure 20-17.5 Sketch Showing Combination Rule 1 in EDA.

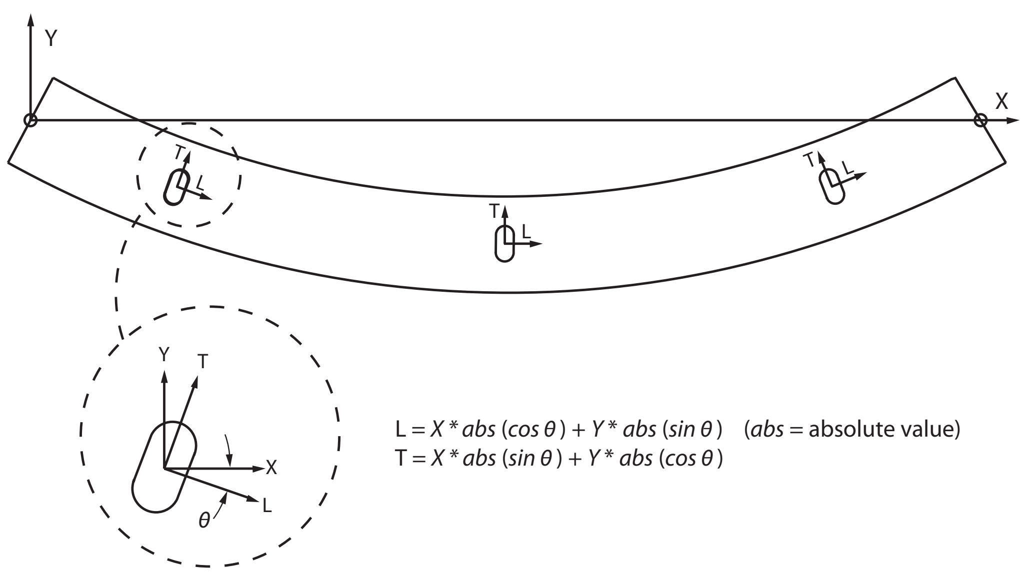
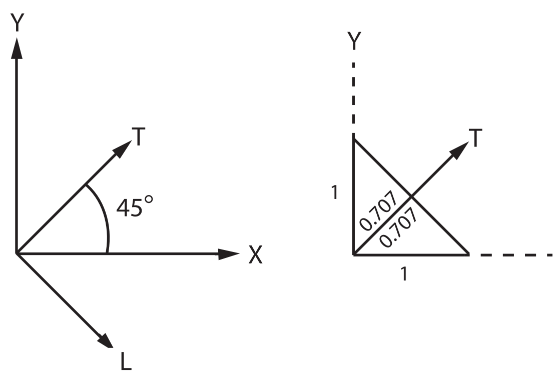


Figure 20-17.6 Sketch Showing Special Case of Coordinate Transformation in EDA.

Example Problem:

The following shows an example of obtaining column displacements in the local axes using the 30% rule, the 40% rule (used in some building codes), and the SRSS rule for an angle of 45° between the global and local axes. The CQC3 method gives the most accurate result, but the equation is too complicated to show in an example problem. Therefore, this example shows the SRSS rule, which equals CQC3 when there is no cross-coupling of modes.



30% Rule

$\Delta_T = (1).707+(.3).707 = 0.92$

40% Rule

$\Delta_T = (1).707+(.4).707 = 0.99$

SRSS Rule

$\Delta_T = \sqrt{.707^2+.707^2} = 1.0$

Equivalent Static Analysis (ESA) Method

In this analysis method, the stiffness of each bent is obtained from a pushover analysis of a simple model of the bent in the transverse direction or a model of the bridge frame in the longitudinal direction that includes the abutment stiffness. The bent and/or the frame stiffness is then used to obtain the fundamental period ($T=2\pi[W/gK]^{.5}$) in the transverse and longitudinal directions respectively. The displacement demand in each direction is obtained from the design response spectra. These two displacements are not combined using any combination rule. For straight bridges the ESA method will give similar results to the EDA method (using either Combination Rule #1 or #2) because the global and the local axes coincide. Curved bridges are straightened in the ESA method and should produce larger (conservative) results because 3-D effects that reduce the demand in the EDA method are lost in the ESA method. Rules for determining whether a bridge should be analyzed using the ESA Method or the EDA Method are provided in SDC Section 2.1.2.

References

AASHTO (2011). AASHTO Guide Specifications for LRFD Seismic Bridge Design, American Association of State Highway and Transportation Officials, 2nd Edition with 2014 Interim Revisions, Washington DC.

Menun, C. and Der Kiureghian, A. (1998). A Replacement for the 30%, 40%, and SRSS Rules for Multicomponent Seismic Analysis, Earthquake SPECTRA, Vol. 14, Number 1, Oakland, CA.

Wilson, E. L. (2004). Static and Dynamic Analysis of Structures, Computers and Structures, Inc., Berkeley, CA.

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