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Seismic performance of skewed and curved reinforced concrete bridges in mountainous states

Thomas Wilson, Hussam Mahmoud *, Suren Chen

Dept. of Civil and Environmental Engineering, Colorado State Univ., 1372 Campus Delivery, Fort Collins, CO 80523, United States

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ABSTRACT

A number of skewed and curved highway bridges have experienced damage or collapse due to seismic events, and has most recently been observed during the Chile earthquake in 2010. In the Mountain West region, bridges integrating skew and curvature are becoming an increasingly prominent component of modern highway transportation systems due to their ability to accommodate geometric restrictions imposed by existing highway components. There is however very little information available on the combined effects of skew and curvature on the seismic performance of Reinforced Concrete (RC) bridges. A comprehensive performance analysis is performed on eight bridge configurations of various degrees of skew and curvature with low-to-moderate seismic excitations which are characteristic of the Mountain West region. Nonlinear time-history analysis is carried out on each bridge configuration using detailed finite element (FE) models. The results show a considerable impact on the seismic performance due to the effects of skew and curvature, with stacking effects observed in the combined geometries. Insights on the complexities of curvature, skew, loading direction and support condition are also made, which may lend themselves to more informed design decisions for practicing engineers in the future.

1. Introduction

Explicit knowledge of the behavioral response of skewed and curved highway bridges to seismic events is essential to designing safe transportation systems. Typically, geometrically complex bridges will exhibit a more complex seismic response as compared to regular, straight bridges.

1.1. Seismic performance of skewed bridges

Although skewed bridges offer many benefits to transportation design, the offset angle of the superstructure has in the past led to seismic-induced failure, particularly due to excessive deflections of the superstructure. The collapse of the Rio Bananito bridge in Costa Rica [1], the Gavin Canyon undercrossing in Northridge [2], and Americo Vespucio/Miraflores bridge in Chile [3], are a few examples of where skew has contributed to seismic induced failures of RC bridges. Failures were typically characterized by in plane rotation of the bridge span about the acute angle of the abutment or pier; often supported by a bearing or seat type support where translational and rotational restraint is minimal. Maragakis and Jennings [4] studied the dynamic behavior of skewed bridges, followed by Wakefield et al. [5] who investigated the failure of the Foothill Boulevard Undercrossing during the San Fernando earthquake in 1971. Failure was characterized by unseating and column damage, attributed to rigid-body motion in the superstructure. Pushover analysis conducted by Bignell et al. [6] showed that the skew angle of the bridge can significantly reduce the comparative ultimate capacity during an earthquake by up to 2/3 in the longitudinal direction. More recently in a study by Saadeghvaziri et al. [7], it was found that seismic-induced impact between spans of skewed bridges can impose large shear stresses on bearings. While the behavior discussed is observed for higher angles of skew; studies have indicated that bridges with skew angles below 30 degrees tend away from higher mode effects, and can be analyzed as straight or represented without using complex FE models [8,9].

1.2. Seismic performance of curved bridges

Curved bridges are susceptible to a similar asymmetrical failure mode as skewed bridges. The effect of curvature on the seismic response of highway bridges has been examined in many studies, although it has been predominantly concentrated on steel bridges [10–15]. Early vulnerabilities in curved bridges were identified through the failure of the I 5/14 Freeway Overpass during the 1971 San Fernando earthquake and subsequent analyses conducted

* Corresponding author.
E-mail addresses: tswilson@rams.colostate.edu (T. Wilson), hussam.mahmoud@colostate.edu (H. Mahmoud), suren.chen@colostate.edu (S. Chen).

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by Williams and Godden [16]. Large excitations were induced in the superstructure of the I 5/14 Freeway causing sections to displace out of shear keys and triggering bending failures in columns bases. Williams and Godden studied the behavior of multispan curved bridges under seismic excitation, and discovered that the inclusion of expansion joints can cause extensive damage through repetitive impacting in translational and torsional modes. More recently, Galindo et al. [13] investigated the effect of four different radii of curvature on the seismic performance of steel I-girder bridges with bearing supports. The study showed that the relative degree of curvature has a significant effect on the bridges response and that for shorter bridge radii there is increased vulnerability to joint residual damage and pounding effects. Unseating was also observed to stem from large rotations in the superstructure causing the deck to rotate off the bearing supports. This is consistent with the findings of He et al. [17], who attributed curvature as the primary parameter affecting seismic load levels at bearing supports and critical cross frame members. From a modeling standpoint, Mwafy and Elnashai [11] assessed the impact of conventional design assumptions on the capacity estimates of curved steel bridges. Modeling of joints, including friction levels in bearing supports, were found to affect the bridges performance and that simplified conservative design decisions can in cases lead to a non-conservative representation of the scenario.

1.3. Seismic performance of curved and skewed bridges

Numerical studies that assess the seismic performance of both skewed and curved bridge geometries were not found in the literature review conducted. Existing research conducted on skew and curvature independently suggests common vulnerabilities. For example, both bridge configurations appear to be susceptible to deck unseating, tangential joint damage, pounding effects as well as large in-plane displacements and rotations of the superstructure. Ultimately, detailed analyses on the seismic performance of curved and skewed bridges are needed to identify specific behavioral vulnerabilities that can lead to improved structural design.

For low seismic hazard regions such as the Mountain West, knowledge of typical vulnerabilities to bridges and earthquake resistant design practices are limited. In the event that an earthquake does occur, it is important to identify vulnerabilities in typical RC bridges in advance, and create a knowledge base for improvement of future bridge designs. In the present study, a parametric analysis is conducted to evaluate the seismic performance of skewed and curved, three-span RC bridges characteristic of the Mountain West region. Detailed FE models are developed and analyzed for eight bridge configurations of various degrees of skew and curvature with consistent structural and geometric components. The bridges examined follow typical design for the region, including the adoption of continuous deck design and integral abutments. Nonlinear time-history analysis is conducted on each bridge configuration under seven sets of earthquake records scaled to a site location in Denver, Colorado. The research is targeted at gaining a better understanding of the global behavior of various bridge configurations during a low-to-moderate seismic event. To better aid design engineers in making informed design decisions, the effects of earthquake input loading direction and abutment support condition, including integral and bearing supports are also examined.

2. 3-D finite element modeling and seismic analysis

2.1. Structural components

The bridges investigated in this study vary in degree of skew and radii of curvature; yet each bridge is constructed with the same structural components. The bridge superstructures (Fig. 1a) are composed of a 205 mm deep concrete slab deck supported by eight 1.73 m deep, parallel pre-stressed concrete I-girders. The girders are reinforced longitudinally near the top, and prestressed near the bottom of each section, with stirrup bracings at 45 cm intervals. End spans are embedded into pier caps creating integral, fixed connections (Fig. 1b). The rectangular pier caps supporting the superstructure are 1.54 m in depth, and are each supported by an interior and exterior pier-column (Fig. 1c). Each column is reinforced with longitudinal rebar, and transverse stirrups that run in alternating directions at a spacing of 41.5 cm. Integral abutments support the superstructure and encase contiguous I-girders, and are reinforced with rebar tied into the deck.

2.2. Development of the finite element models

The structural performance of the bridges selected for this study are evaluated using 3-D FE models constructed in SAP2000 [18]. The bridge deck is modeled using thin shell elements that span intermediate nodes of the girders and are further meshed into quadrants. Frame elements capture axial, shear, and bending deformations, and are used to model the abutments, girders, bent caps, and pier-columns. Concrete confinement of the pier-columns is based on the model developed by Mander et al. [19]. Prestressing tendons are modeled as equivalent loads (after losses) and follow the geometry of tendons at each girder. Girders are connected to shell elements by use of fully constrained rigid links. The columns are fixed at the soil foundations in all rotational and translational degrees of freedom (DOF). In order to account for inelastic column behavior in the substructure, plastic hinges are implemented at the top and bottom of the pier-columns (Fig 1b). The plastic hinges in the columns utilize a lumped plasticity model that is based on a force-biaxial moment (PMM) interaction. The PMM interaction hinges account for axial force fluctuations and bending in orthogonal directions of the targeted member, as well as degradation behavior and ductility estimation.

The abutment–girder connections are modeled using rigid links that are characteristic of the integral fixity between the abutment and girder. The abutment is considered to have fixity from the surrounding soil and pile foundation in all DOF except the longitudinal. The backing soil behind the abutment is represented by the use of a multi-linear, longitudinal, compressive spring (Fig. 1b) following the Caltrans design procedures for backing soil behind an integral abutment [20]. The stiffness is based on passive earth pressure tests and force deflection results derived from large-scale abutment experiments [21] with equations refined by Shamsabadi et al. [22].

2.3. Ground motion selection and scaling for mountainous states

Seven sets of earthquake records are selected in accordance with the AASHTO Guide Specifications for LRFD Bridge Design from the Pacific Earthquake Engineering Research (PEER) Center strong motion database [23,24]. To simulate typical earthquake ground motion for states in the Mountain West region, Denver, Colorado is chosen as a prototype site location. A stiff soil profile for Denver is selected, and a design response spectrum is developed using the USGS database and AASHTO Guide Spec. Strong motion records are chosen based on a moment magnitude range between Mw 6.5 and 7.0, a stiff soil condition with shear wave velocity range of 300–550 m/s, and a 20–30 km range for the Joyner–Boore distance to the fault (Rjb). The characteristics of the selected ground motions are listed in Table 1. Fig. 2 shows the response spectra for the fault normal component of the selected records, and the design response spectrum developed for the site condition. The scaling factor is computed for the fault normal and parallel directions by matching the AASHTO design response spectra to the average of the seven