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Research Article

Nonlinear Seismic Response Analysis of Curved and Skewed Bridge System with Spherical Bearings

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A three-dimensional (3D) modeling approach to investigate nonlinear seismic response of a curved and skewed bridge system is proposed. The approach is applied to a three-span curved and skewed steel girder bridge in the United States. The superstructure is modeled using 3D frame elements for the girders, truss elements for the cross-frames, and equivalent frame elements to represent the deck. Spherical bearings are modeled with zero-length elements coupled with hysteretic material models. Nonlinear seismic responses of the bearings subjected to actual ground motions are examined in various directions. Findings indicate that the bearings experience moderate damage for most loading scenarios based on FEMA seismic performance criteria. Further, the bearing responses are different for the loading scenarios because of seismic effects caused by interactions between excitation direction and radius of curvature.

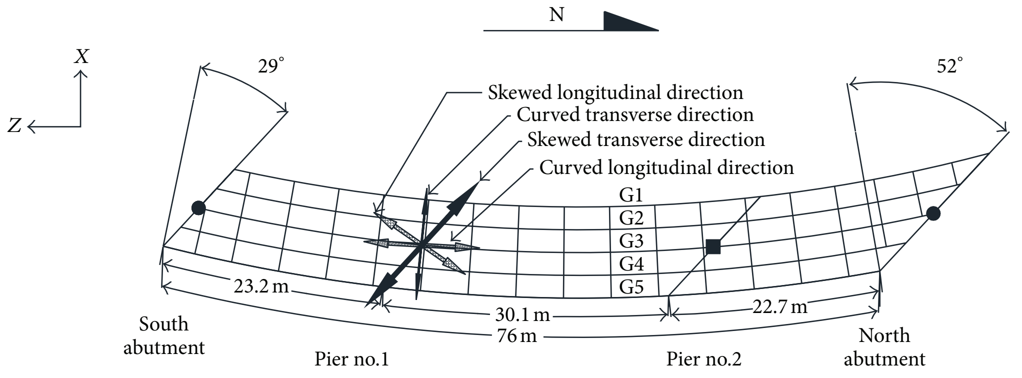
1. Introduction

Studies related to the design and analysis of curved and skewed steel bridges have focused on modeling and design for static and pseudo-static loads [1–4], and only a few investigations have looked at seismic behavior [5]. To design and assess curved steel bridges in high and moderate seismic zones, it is of interest to more extensively examine seismic analysis methods so that reliable 3D modeling approaches are developed. Studies have been undertaken that applied modeling approaches to predict the seismic response of straight steel girder bridges [6]. Similar simplified modeling approaches have been proposed for curved steel bridges, but the approaches were applied to static events [1]. These studies have shown that modeling using a 3D approach can provide improved accuracy relative to line girder analyses by incorporating member depths. For a curved and skewed bridge, where significant lateral displacements may be induced at the bearings under a seismic event, modeling structural component depths would be assumed to be important.

For these reasons, a 3D modeling approach is used herein to investigate seismic responses of a curved steel I-girder bridge system with skewed supports. The 3D approach is applied to a three-span continuous curved steel I-girder bridge system in the United States. Following the approach recommended by previous research [1], the bridge is modeled using elastic frame elements for the I-girders, truss elements for the cross-frames, and elastic frame elements for the deck. Preliminary seismic responses at the bearings are presented for the bridge under El Centro ground motions.

2. 3D Modeling Approach

All elements used for 3D model were generalized using OpenSees [8]. Curved bridge framing was represented using frame elements with lumped masses being placed at each node, with those masses calculated using tributary dimensions. Model construction initiated with calculation of superstructure and substructure section properties. Superstructure included girder, cross frame, concrete deck, and rigid link element, while substructure included pier column, cap, abutment, and footing. Spherical bearings were modeled in OpenSees using ZeroLength elements. All rotational degrees



● Restrained from transverse movement
■ Restrained from longitudinal movement
Note: All other bearings are free to move in longitudinal and transverse directions

Figure 1: Studied bridge framing plan [5].

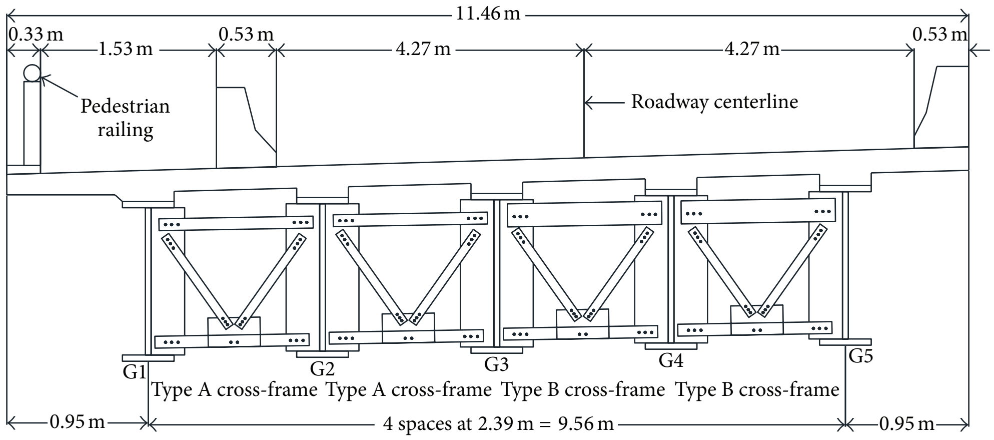


Figure 2: Typical bridge cross-section.

of freedom for the bearings, which accommodated rotations about various axes, were unrestrained. To simulate the bearings' moment-rotational behavior, a combination of different material models available in OpenSees was utilized. Appropriate nominal material properties were used for the steel and concrete.

3. Application to the Selected Bridge

3.1. Bridge Description. The bridge used for the study is a curved and skewed steel I-girder bridge located in Pennsylvania. The three-span continuous bridge has radius of curvature of 178.49 m and is composed of five ASTM A572 grade 50 steel plate girders with an abutment skew that varies between 29° and 52° (south to north) relative to the traffic direction as shown in Figure 1. Bridge support conditions are as shown in Figure 1. This figure shows that two bearings are restrained from transverse movement, one bearing is restrained from longitudinal movement, and all other bearings are free to move in both the longitudinal and transverse directions. Girders are spaced 2.39 m center-to-center as shown in Figure 2. All girders have 1219 mm × 13 mm webs with 356 mm wide top and bottom flanges of varying thickness as shown in Table 1. Two different K-shaped cross-frame types are used in the bridge. Type A top and bottom chords are composed of 3.5 × 3.5 × 3/8 double angles. Type A diagonals are 3.5 × 3.5 × 3/8 angles. Type B top chords are WT14 × 49.5 s, and type B bottom chords are 3.5 × 3.5 × 3/8 double angles. Type B diagonals are composed of 3.5 × 3.5 × 3/8 angles. The superstructure is supported by multi-circular column piers with 914.4 mm wide by 1066.8 mm deep reinforced concrete pier caps [5]. Concrete pier columns on the foundation wall which is 11.9 m long, 3.4 m wide, and 0.7 m thick are spaced 4.0 m apart. The abutments are supported by the spread footings with a 1.6 m tall backwall. More detailed description of the substructure units can be found elsewhere [5].

3.2. Spherical Bearings. Spherical bearings have been utilized to support curved and skewed steel bridge superstructures

(a) General view (b) Detailed view

Figure 3: Spherical bearing system.

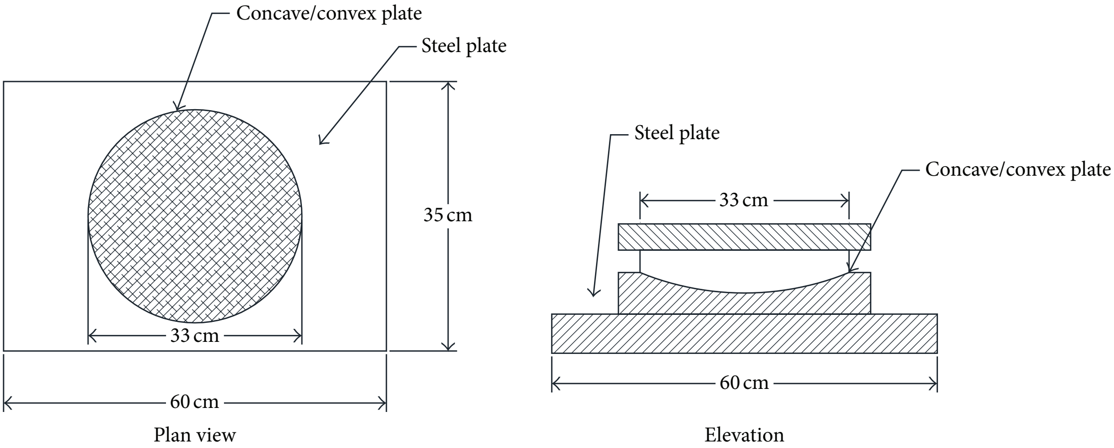


Figure 4: Spherical bearing details.

Table 1: Steel plate girder element dimensions (width × thickness).

Girder	Top flange (mm)	Web (mm)	Bottom flange (mm)
G1, G2	356 × 16	1219 × 13	356 × 25
G3, G4, G5	356 × 16	1219 × 13	356 × 32

to accommodate rotations that may occur about more than one axis. They are used in the curved bridge being examined herein. In general, bearings are divided into two main categories, fixed and expansion. A fixed bearing permits rotational movement and prevents translation in one or more directions, while an expansion bearing permits both rotation and translations. A spherical bearing fixed in the longitudinal direction exists for middle girder G3 at interior pier no. 2 (see Figure 1), and spherical bearings fixed in the transverse direction exist for G3 at the abutments. All other locations had spherical expansion bearings that are free to move in both the transverse and longitudinal directions. Figure 3 shows representative bearings used in the curved bridge, and Figure 4 illustrates spherical bearing details.

3.3. 3D Model. The superstructure of the curved steel bridge was idealized based upon the proposed 3D modeling approach in OpenSees [8]. Figure 5 shows the 3D curved bridge model. The mesh consists of steel girders and the concrete deck modeled using elastic beam column elements. These elements were used because they were developed to simulate 3D beam behavior, including biaxial bending and torsion. Small straight sections were used to simulate the curvature of the girders and concrete deck. Nodes were placed at cross-frame locations. Longitudinal and transverse elements that represent the behavior of the slab were used. Member properties that reflect the slab dimensions were used along with appropriate steel girder and cross-frame properties in the model. Boundary conditions were implemented based on actual support conditions and attempted to account for spherical bearing moment-rotational behavior. This behavior was modeled in OpenSees using Steel01 and hysteretic material models in parallel as shown in Figure 6(a). The spherical bearings used in the bridge were made of A36 steel and the Steel01 material reflecting a bearing having an initial stiffness, K_e, of 200 GPa and a strain-hardening ratio, b, of 0.014. To approximate nonlinear hysteretic behavior, the hysteretic material model used four linear stiffness functions, including an initial stiffness, K_1, of 312.5 GPa, a second stiffness, K_2, of 3 GPa, a third stiffness, K_3, of 1.25 GPa, and a final stiffness, K_4, of −312.5 GPa. All stiffness values were determined via a

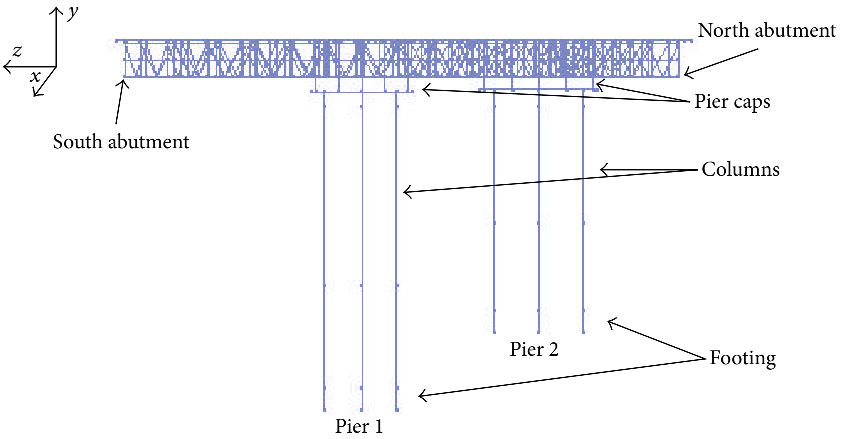


Figure 5: 3D bridge model.

trial and error procedure that compared model predictions to actual data from Roeder et al. [7] that examined spherical bearing under cyclic loads. Figure 6(b) shows a comparison between experimental and analytical moment-rotational hysteresis loops. In this figure, the analytical model provides reasonable approximation of real bearing behavior at 10,000 cycles. Substructure units, including the pier columns and caps, abutment, and footings, were idealized in the 3D OpenSees model following recommendations by Nielson [6]. Included in the substructure models were the pier columns and caps, abutments, and footings. The detailed modeling description for the substructure can be found elsewhere [5].

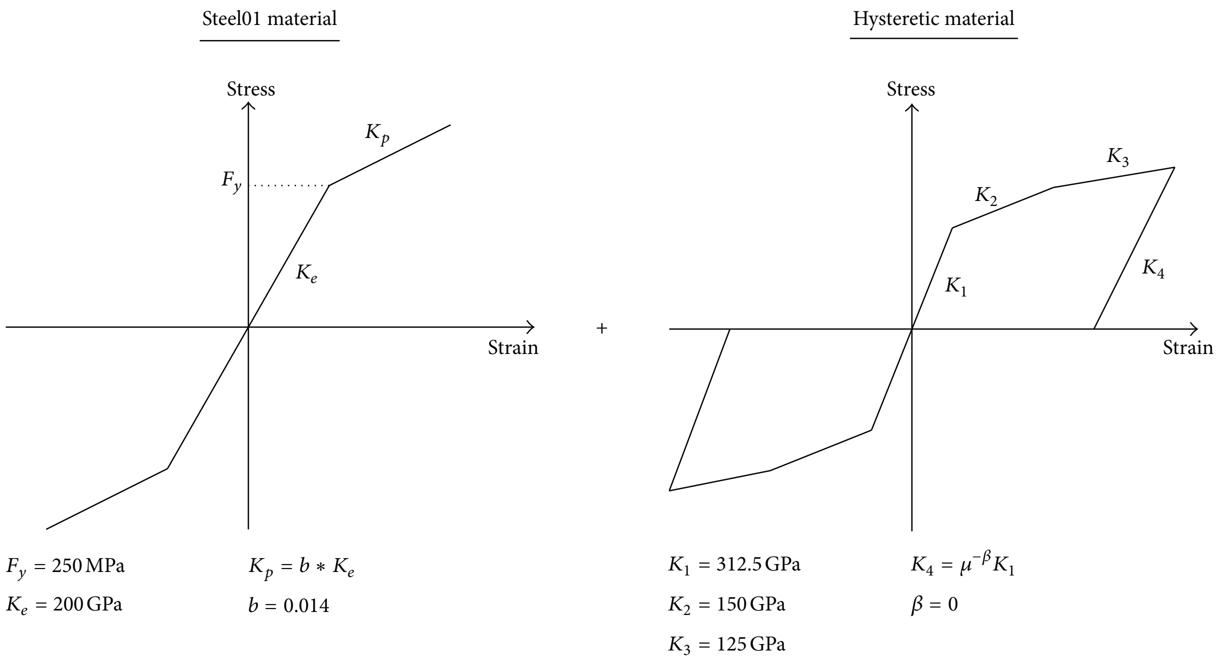
4. Seismic Response of Curved and Skewed Bridge

Preliminary results from seismic analyses of the curved and skewed bridge using the 3D model are presented. These results focus on seismic bearing response as a result of longitudinal and transverse earthquake loadings.

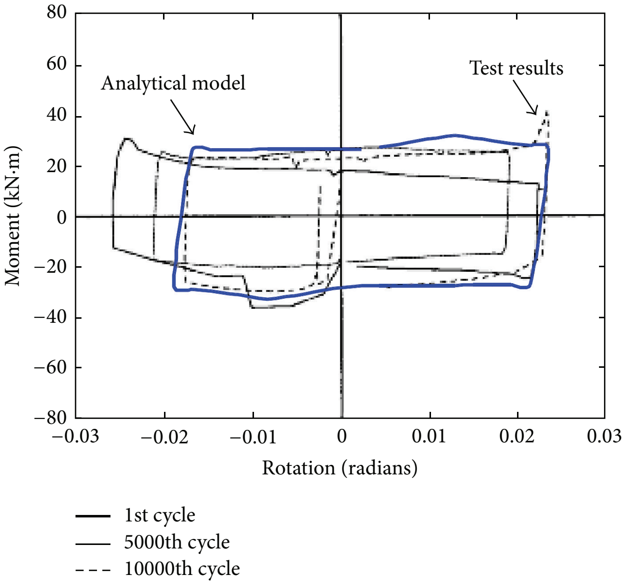
4.1. Curved and Skewed Longitudinal Earthquake Loadings. Since the structure being examined is horizontally curved and rests on skewed supports, directions both parallel to and perpendicular to the skewed supports were identified as those for the ground motions. Applying ground motions in this fashion has been shown to be preferred for inducing critical skewed bridge response [9, 10]. To apply these motions, two "longitudinal directions" were defined. The direction tangential to the chord of each curved girder at the abutment and/or pier was referred to as the "curved longitudinal" direction as shown in Figure 1. The direction perpendicular to substructure units at each bearing was referred to as the "skewed longitudinal" direction as shown in Figure 1. To capture critical superstructure response, El Centro ground motions, which had a peak horizontal ground acceleration of 0.313 g, were applied to the bridge in the curved longitudinal direction initially and then the skewed longitudinal direction. Bearing rotations were examined at all supports while the earthquake loading was applied to the bridge. Existing literature indicates that these rotations provide key information in relation to assessing bridge susceptibility to earthquake damage [11].

To explore seismic behavior in the curved longitudinal direction, bearing rotations were monitored in the global x-axis direction as shown in Figure 1. Figure 7(a) shows the seismic response of a representative spherical bearing when acted on by the curved longitudinal earthquake loading. The response of this fixed spherical bearing, located underneath G3 at the south abutment, depicts rotations about the x-axis direction exceeding -0.02 radians. Seismic responses for the spherical bearing subjected to the skewed longitudinal earthquake loading are shown in Figure 7(b). As expected, rotations about the x-axis are different when the bridge is acted on by skewed and curved longitudinal earthquake loadings because of different seismic bending-torsion coupled effects being enacted based on relationships between the excitation direction and the girder radius of curvature. The hysteresis loop shown in Figure 7(b) depicts rotation about the x-axis exceeding -0.03 radians and moments beyond 30 kN-m, values that would classify this bearing as being slightly damaged based on existing research (greater than ± 0.02 radians) if those rotations exceeded any existing clearance in the bearing [7]. In addition, it has been stated that a spherical bearing having rotations exceeding -0.03 radians may moderately damage an abutment or pier [11].

4.2. Curved and Skewed Transverse Earthquake Loadings. The transverse direction perpendicular to the chord of each curved girder at the abutment and/or pier was referred to as the "curved transverse" direction as shown in Figure 1. The direction parallel to substructure units was referred to as the "skewed transverse" direction as shown in Figure 1. Similar to the curved and skewed longitudinal earthquake loading cases, El Centro ground motions were also applied to the bridge in the curved and skewed transverse directions. Figure 8(a) shows the seismic response of the spherical bearing due to the curved transverse El Centro ground motions, again presented as moment-rotation hysteresis curves. The



(a) Spherical bearing OpenSees model components modeled in parallel



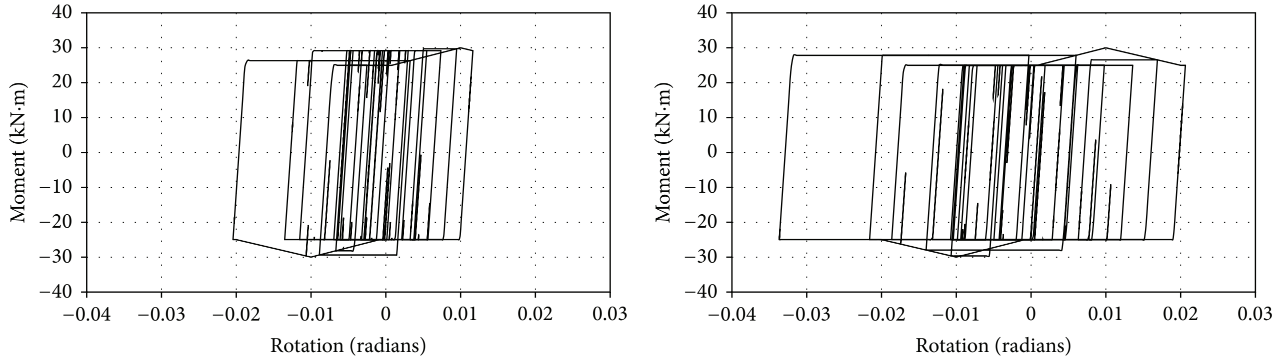
(b) Moment-rotation behavior [5, 7]

Figure 6: Spherical bearing model.

hysteresis loop shown in Figure 8(a) depicts rotations about the x-axis direction exceeding −0.03 radians and moment greater than 30 kN-m. Again, this could be classified as moderately damaged according to FEMA [11]. The hysteresis loop shown in Figure 8(b), which examines bearing response when the bridge is subjected to the skewed transverse ground motions, depicts rotation about the x-axis direction reaching around −0.01 radian and moment of approximately 30 kN-m, values that would be indicative of slight damage according to FEMA [11]. In similar fashion to the longitudinal earthquake loading cases discussed earlier, moment-rotation relationships for the spherical bearing were different between the skewed and curved transverse earthquake loading cases, due to the different behavior being attributed to relationships between the loading direction and radius of curvature.

5. Conclusions

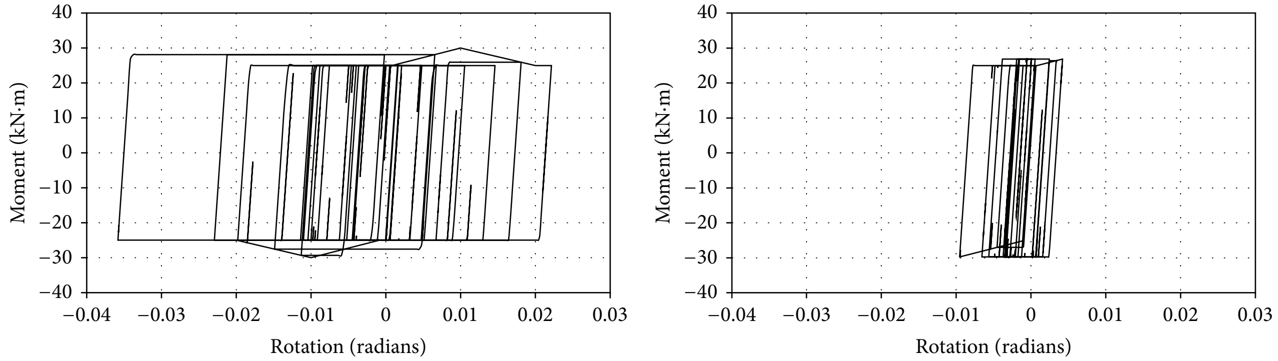
Limited consideration has been given to seismic design and detailing of a curved steel bridge having skewed supports. The primary goal of this study was to investigate the seismic



(a)

(b)

Figure 7: G3 spherical bearing moment-rotation response at the south abutment for (a) curved longitudinal direction and (b) skewed longitudinal direction.



(a)

(b)

Figure 8: Spherical bearing response at the south abutment for (a) curved transverse direction and (b) skewed transverse direction.

bearing response of a curved and skewed steel I-girder bridge system using the 3D modeling approach being proposed in this study. Specifically, moment-rotation response relationships for representative spherical bearings were examined when a selected horizontally curved and skewed bridge was subjected to El Centro ground motions. Rotations of these spherical bearings appeared to exceed −0.03 radians when the bridge was subjected to the skewed longitudinal and curved transverse ground motions. Therefore, these bearings may experience moderate damage under the imposed ground motions based upon FEMA criteria (2003). In addition, bearing response differed for the considered earthquake loading scenarios because of different seismic bending-torsion coupled effects being enacted based on relationships between the excitation direction and radius of curvature.

Acknowledgments

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