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Comparison of curved prestressed concrete bridge population response between area and spine modeling approaches toward efficient seismic vulnerability analysis

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A R T I C L E I N F O

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This paper presents two finite element modeling approaches for seismic evaluation of curved precast-prestressed concrete (PSC) I-girder bridges and compares the results in a statistical and graphical manner. These approaches, including area and spine models, were applied to a simply-supported, curved PSC I-girder bridge under an ensemble of 3D synthetic ground motions. Along with performing non-linear time history (NLTH) analyses of the bridge to capture its separate seismic response, the efficiency of each approach was evaluated with respect to execution time and each was compared. This comparison reveals that the seismic responses that were computed at low computational cost from the spine approach are reasonably analogous to those from the area model. Seismic fragility curves of a portfolio of curved PSC bridges using the spine approach are also created to assess their vulnerability and then compared to those gained from past studies. This comparison shows a reasonable agreement for the PSC portfolio.

1. Introduction

Bridges are considered the most vulnerable elements in the national transportation networks of the United States during an earthquake [5,9,2]. In case of bridges designed without sufficient seismic detailing, it has been reported from past earthquakes [7,19] that there has been significant damage on particular components of the bridges that were observed across regions in the United States. Describing the probability of earthquake-induced bridges experiencing different damage states has been vital to treat uncertainty related to their characteristics and incorporate randomness in seismic excitations. A fragility curve has been commonly used to quantify the probability of bridge damage or failure and vulnerability due to seismic loadings [33,20,23].

The majority of studies for seismic vulnerability assessments of bridges have focused on regular bridges in the form of fragility curves [7,19,21,22,11,12,14]. However, there exist a significant number of existing bridges with irregular configurations nationwide. Since irregular configuration factors in a bridge unfavorably affect its seismic behavior and vulnerability [15], pertinent bridge design codes, such as the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Seismic Bridge Design [1] have dealt with requirements associated with the irregularities. Curved precast-prestressed concrete (PSC) I-girder bridges that have been regarded as one of the representative irregular bridge types have frequently been constructed in both seismically active and moderate seismic regions as the complexity of traffic flow transitions and the efficiency of transportation network increases.

As stated above, several seismic vulnerability studies [7,18], for straight PSC I-girder bridges and their retrofits [21,22] to seismic excitations have been performed. Specifically, Choi et al. [7] and Nielson and DesRoches [18] examined seismic response of various straight PSC I-girder bridge configurations and types. It was found that simply supported straight PSC I-girder bridges exhibited seismic fragility and potential damage under moderate ground motions. Padgett and DesRoches [23] proposed a methodology for the establishment of analytical fragility curves in part for straight PSC I-girder bridges with different retrofit measures. Though these studies have successfully assessed seismic vulnerability of straight PSC I-girder bridges, these findings are not applicable to curved PSC I-girder bridges due to their unique features and system mechanisms under seismic excitations.

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Recent studies [29,28,30–34,3] demonstrated that steel bridges with irregular configuration factors such as radius of curvature have more significant damage due to excessive torsional response than regular bridges. For example, Seo and Linzell [29–31] have attempted to examine the seismic response and vulnerability of curved steel girder bridges using conventional three dimensional (3D) finite element models. These models required more complex computational solutions coupled with risk analysis for inherent randomness in earthquakes in conjunction with uncertainty related to irregular characteristics than straight ones. It was demonstrated that each curved steel bridge has distinctive characteristics, leading to different seismic responses affecting its vulnerability. The significant finding from the work [30,31] was that the curved steel bridges produced fairly higher seismic vulnerabilities than those for straight ones due to their curvatures associated with the other parameters. Based upon the literature review, unfortunately significant studies related to seismic evaluation and vulnerability of curved PSC I-girder bridges have not been found. To better understand seismic behavior and vulnerability of curved PSC bridges at reasonably low computational cost using 3D finite element models, the need of developing a new seismic modeling technique for such bridge populations that enables its efficient seismic vulnerability assessment with variability in their bridge characteristics is of significance.

The current study focuses on developing a finite element analysis modeling technique for seismic vulnerability assessment of PSC I-girder bridges in a more efficient manner. To accomplish the goal of this study, two 3D finite element modeling approaches, including a spine model and an area model, were developed and applied to a curved two-lane, simply supported PSC I-girder bridge. The responses of both models of the bridge were compared statistically and graphically. The bridge was designed using current AASHTO codes [1] and PCI (Precast/Prestressed Concrete Institute) practices [24]. Nominal materials and components for bridge construction were selected for use in the design. The 3D models were loaded with an ensemble of synthetic ground motions having two horizontal and one vertical acceleration components. These ground motions varied in magnitude and intensity to make it possible to run a broad spectrum nonlinear time history analysis of seismic response. The effect of model approach on the seismic response is also examined, along with comparing efficiency of the analysis. To validate the possibility of creating seismic fragility curves, component- and system-level fragility curves for a suite of 15 curved simply supported PSC I-girder bridges that were also designed following the AASHTO and PCI specifications were developed using a spline model and compared to those developed in past studies of straight ones.

2. Structural design of curved PSC girder I-girder bridge

A curved PSC I-girder bridge was initially chosen and designed to examine its seismic response and susceptibility and to explore the differences between area and spine models. The bridge design complied with the [1] LRFD Bridge Design Specifications [1] following the procedure outlined by the Precast/Prestressed Concrete Institute Bridge Design Manual [24]. It was assumed that the bridge is located in the central United States that would be considered Seismic Zone 1 where design considerations for seismic performance are minimal. These requirements are described in the AASHTO Specifications. The abutment type for these bridges is the seat-type abutment. Integral abutments are generally not favorable for curved bridges [16]. Elastomeric pads each with two embedded steel dowels were selected for use in both fixed and expansion bearings. The AASHTO I-girder type III was used based on established design requirements. Each girder is prestressed with strands of tensile strength of 1860 MPa and is 13 mm in diameter. Both straight and harped strands are employed. The concrete cast in place deck is 200 mm thick.

The bridge has the following attributes: the span was 23 m and width was 9.8 m so that four girders were deemed appropriate; the girders used 24 straight tendons and 8 harped tendons; the radius of curvature was 402 m; and an offset of 160 mm was developed at the mid-span centerline as a result of the curvature and span length. This with its design schematic can be illustrated in Fig. 1. The offset is the distance between the centerline and the arc chord of curvature at mid-span. Eq. (1) will determine the offset as follows:

$$O = \frac{L^2}{8R} \tag{1}$$

where O, L, and R is the offset, span length, and radius of curvature, respectively. Concrete cast-in-place diaphragms were 160 mm thick and placed at the midspan and endspan. The seat type abutment was anchored by 8 cast-in-place concrete piles of 400 mm in diameter. A 75 mm expansion gap was located at each abutment-deck interface.

3. Finite element modeling approach

Two modeling approaches, encompassing the area and spine models, were presented on the bridge type using the program CSI-Bridge [8]. It is important to note that area and spine modeling is a general term that can describe many different models. The models described in this study were specific to the finite element modeling approaches used for the seismic response and fragility investigation of curved PSC bridges and were categorized into area and spine as appropriate. The spine modeling approach is one that models a superstructure with beam elements, while the area model approach use plate elements or shell elements to idealize it. The following subsections describe each approach for the superstructure and the modeling for the substructure with bearings for both approaches.

3.1. Area model for superstructure

The area modeling approach is the more complex of the two approaches in the current study. The superstructure model is constructed using shell and frame elements. Prestress tendons representing the Gr. 270, 7-wire strands were modeled using frame elements located within each girder. Tendon prestress force is 1100 MPa after all losses, including elastic shortening, steel relaxation, creep, and shrinkage. Both harped and straight tendons were modeled and placed in the correct position relative to the girder according to the structural design.

Each girder was represented by frame elements with the cross section of a Type III girder that span between the supports. The concrete compressive strength of the girder is 48 MPa. Shear reinforcement consists of #10 (#3 imperial) stirrups that were placed appropriately according to structural analysis. These frame elements were assigned the correct cross section and material properties of the girders specified during the designing process. The bridge deck was idealized using shell elements. Maximum length of a particular shell element is 3.05 m. Increasing this length decreases the number of joints and vice versa. The deck section shell elements represent a 200 mm slab thickness consisting of 27 MPa concrete. Note that a shell elements are three or four-node area objects used to model membrane and plate-bending behavior and are useful for simulating bridge deck systems [8].

Diaphragms were also modeled using shell elements with corner nodes at adjacent girder frame elements; thus, with four gird-