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Seismic vulnerability of skew bridges under bi-directional ground motions

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ABSTRACT

Past earthquakes have demonstrated that skew bridges are more vulnerable to earthquake induced failure than a normal bridge due to their complex load transfer mechanism. This study deals with the effect of skew angle on seismic vulnerability of these bridges under horizontal two-component (bi-directional) ground motions. For this purpose, representative models of two-span simply supported, typical highway overpasses with varying skew angles have been considered. Finite element models of these bridges, which have been designed using modern seismic provisions, are developed using a widely used software. A suite of bi-directional ground motions with varying strong motion properties and representing different hazard levels is used for nonlinear dynamic analysis and subsequent seismic vulnerability estimation using fragility curves. Deck unseating and damage of columns are considered as the damage measures for the vulnerability analysis. The effect of ground motion directionality on the vulnerability of bridges has also been investigated in this study. Results of this study indicate that as the skew angle increases, there is an increase in the probability of failure for a given ground motion intensity. It is also found that the dispersion of fragility curves for bi-directional ground motions can be minimized by using the square root of sum of squares (SRSS) of peak ground acceleration (PGA) of all components than the PGA of any component.

1. Introduction

Owing to the requirement of straight highways for speed and safety considerations and space constraints, it is often not possible to align the piers exactly normal to the longitudinal axis of a bridge deck. These conditions lead to an arrangement in which piers are not normal to the longitudinal axis of a bridge but have some degree of skewness. Nowadays these skew bridges have become the backbone of modern transportation system in many cities. The skewness of piers in bridges results in a different load transfer mechanism in the bridge structure compared to a normal bridge. Past failure incidents have demonstrated that the skew bridges are more vulnerable to the damage induced by seismic forces than that of a normal bridge. Wakefield et al. [1] in their study on skew reinforced concrete (RC) bridges mentioned that the skewness results in a reduction of the effective span and thus, improves the load carrying capacity of a skew bridge than a normal bridge under static loads. However, in case of dynamic loading, this skewness can result in a response amplification of bridges. Therefore, these skew bridges need special attention under seismic loads than normal bridges.

A significant amount of research work has been done so far on static and dynamic behavior of skew bridges. These studies either considered various damage patterns using simple to complicated analytical models or data obtained from real-life case studies after a seismic event. Many of these studies have been carried out particularly focusing on modeling of bridge decks. For example, to consider the translation and rotational modes, Maragakis and Jennings [2] modeled the deck with simple rigid rod; Ghobarah and Tso [3] used beam model to take into account the flexural and torsional modes of the deck; Wakefield et al. [1] considered more complex built up plate model for the bridge deck. Meng and Lui [4] focused on the superstructure flexibility, substructure boundary conditions, structural skewness and stiffness eccentricity in their model. An approximate hand-method for dynamic analysis of a skew highway bridge with continuous rigid deck was proposed by Kalantari and Amjadian [5]. Kaviani et al. [6] presented a detailed approach for modeling reinforced concrete bridges with skew-angled seat-type abutments and studied their seismic behavior. From the aforementioned studies, it can be concluded that the skew bridges are susceptible to excessive in-plane rotation and longitudinal and transverse displacements making them more

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vulnerable to damage including deck unseating than similar normal bridges. In fact, past earthquakes have demonstrated that major damage in bridges may occur due to deck unseating [7–13].

Seismic fragility analysis of any structure gives very useful information in predicting damage of the structure for a future seismic event, which can be used for loss estimation, retrofitting decisions, and future planning. Using representative numerical models as well as damage data from previous earthquakes, seismic fragility analysis for bridges have been carried out in the past. Shinozuka et al. [14] performed a comprehensive study on statistical analysis of fragility curves and developed both empirical and analytical fragility curves for bridges. Deformation based vulnerability functions are derived for RC bridges by Elnashai et al. [15] and extended to implement on classes of bridges using a generic relationship. Karim and Yamazaki [16] obtained a correlation between fragility curve parameters and over strength ratio of structures and developed a method to construct fragility curves for non-isolated highway bridges in Japan. Combined fragility curves for four classes of bridges in the central and southeastern United States are developed in a study by Choi et al. [17]. Tavares et al. [18] developed bridge-system fragility curves by considering different classes of bridges based on their superstructure material and construction type in eastern Canada. Bignell et al. [19] performed a seismic vulnerability assessment on a number of wall pier supported highway bridges with varying bridge characteristics such as wall pier type, number of piers, skew angle, type of foundation, concrete reinforcement ratio, bearing type, and wall height. Effects of bridge curvature on the seismic vulnerability of bridges was considered by Seo and Linzell [20]. Fragility analysis of long-span bridges was done by Seo and Caracoglia [21] to analyze monetary losses, produced by wind loading. For bridges with skew angles of 0°, 12.33° and 45°, Pottatheere and Renault [22] developed fragility curves considering different damage states ranging from slight damage to complete collapse. They mainly emphasized on fragility analysis of bridge piers and bearings in their study. Sullivan and Nielson [23] focused on the fragility analysis of multi-span simply supported skew bridges and concluded that skew angles under fifteen degrees do not affect the bridge response to a great extent. However, larger skew angles may result in more fragile bridge systems. Seismic response of pounding skew bridges that involve oblique frictional multi-contact phenomena was studied by Dimitrakopoulos [24]. The study concluded that the tendency of these bridges to show transverse displacements and/or rotations (and hence unseat) after deck-abutment collisions is a factor of the bridge plan geometry and friction along with the skew angle.

In the aforementioned seismic vulnerability studies, the fragility analysis of skew bridges was primarily limited to the bridge pier columns and bearings and no or less emphasis was given to the deck unseating phenomenon, although previous studies have pointed out that skew bridges may be highly susceptible to such phenomenon under dynamic loadings. The effect of ground motion directionality has also been studied by many researchers considering different structural models [25–32]. Most of these studies used the PGA of a single component of a ground motion as an intensity measure for fragility analysis. However, this intensity measure may not be an effective one for fragility analysis when dealing with ground motions having more than one components. As per the authors' knowledge, no work has been carried out so far on fragility analysis of bridges under bi-directional ground motion with a particular emphasis on the vulnerability of skew bridges for different failure mechanisms.

In this study, seismic vulnerability analysis of typical highway overpass bridges with varying skew angles has been performed with a core attention towards the column and deck unseating damages as well as the directionality effect of ground motions. For this purpose, numerical models of a two-span simply supported bridge with varying degree of skewness have been developed. These bridges have been designed using modern seismic provisions. An eigenvalue analysis has been carried out to study the effect of skew angle on natural periods and mode shapes of different models. For seismic analysis, bridge models are subjected to 30 bi-directional (horizontal two-component) ground motions categorized in three different hazard levels under two cases of ground motion directionality. In the first case, the first component of the motion is applied along the longitudinal direction of bridge, while the second component is considered in the transverse direction. In the second case, the first and second components of the same ground motion are interchanged for application in the longitudinal and transverse directions of the bridge models. The first and second cases henceforth will be termed as Case I and Case II, respectively. First, nonlinear time history analyses have been performed to obtain the responses of the bridge models for both cases of ground motion directionality. After that, fragility curves are obtained for column and deck unseating damages and the effect of ground motion directionality on the fragility of bridges has been investigated. Finally, an attempt has been made to identify the best PGA related intensity measure for bi-directional ground motions in order to reduce the dispersion of bridge fragility.

2. Numerical modeling

Numerical modeling of the bridges is done in the finite element software SAP 2000, v14.0.0- Advanced [33]. Different models representing a normal bridge (i.e., skew angle 0°) and four skew bridges with skew angle of 15°, 30°, 45° and 60° are developed. All the models have the same span and deck width (i.e., two equal spans of 20 m each and an overall width of 14.18 m measured along the skew direction). One end of each span (intermediate end) is supported on a bent consisted of three reinforced concrete columns and the other end is supported on the seat type abutments. The superstructure is modeled as a reinforced concrete continuous deck slab of 40 m length and 250 mm thickness in the supported part, which becomes 260 mm for the overhanging part. Superstructure is further supported on six reinforced concrete T-beam girders having a cross section dimension of 1.5 m $\times$ 0.45 m. Fig. 1a shows a schematic diagram of the cross section of T-beam deck slab. For modeling, the contribution from abutment stiffness and soil-structure-interaction effects are assumed to be negligible. All columns are assumed to be fixed at their bases similar to a few previous studies [34,22,35]. Although abutment stiffness and soil-structure interaction may play a significant role in the dynamic response of a bridge, the reasons behind these assumptions are: (i) a stiff site condition has been assumed for this study and (ii) for simplicity of analysis [22] while the focus is mainly on the comparison of bridge responses with different skew angles.

For the seismic design of the bridges, the AASHTO-LRFD [36] bridge design specifications are used along with IBC [37] design spectrum corresponding to a site with stiff soil condition in Los Angeles area. Each column in all models is designed to meet the imposed seismic load based on the chosen design spectrum. The columns are of circular cross section with diameter of 1.7 m for normal, 15° and 30° skew bridges, and 1.8 m and 1.9 m for 45° and 60° skew bridges, respectively. Owing to the increased force demand for bridges with larger skew angles, larger column sizes are chosen for bridges with higher skewness. Same pattern of reinforcement detailing is used for all the columns and is shown in Fig. 1b. Transverse spacing between the columns in all models is kept such that the projected spacing along the direction perpendicular to the longitudinal direction is 5 m. Thus the actual transverse spacing among the columns in all the skew models is decided by