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Seismic fragility analysis of skewed bridges in the central southeastern United States

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ABSTRACT

Skewed bridges are often encountered in the highway bridge system when the geometry cannot accommodate straight (unskewed) bridges. The objective of this study is to investigate the influence of skew angle on the seismic response of bridges using nonlinear time-history analysis and probabilistic seismic assessments. Six types of skewed and straight bridges (including multi-span simply supported, multi-span continuous, and single-span skewed bridges with steel or concrete girders together with non-integral abutments) commonly used in the central and southeastern United States (CSEUS) are considered for establishing three-dimensional numerical bridge models. The six bridge types are further categorized as: (1) non-seismically designed (NSD) bridges, (2) bridges with seismically designed (SD) columns, (3) bridges retrofitted by (i) column jackets, (ii) isolator bearings (IBs) and keeper plates (KPs), (iii) restrainer cables (RCs) and shear keys (SKs), or (iv) seat extenders (SEs) and shear keys (SKs). Probabilistic seismic demand models incorporating geometric and material uncertainty parameters for the bridges under a suite of ground motions are established to develop corresponding sets of fragility curves in terms of vulnerable bridge components. System fragility curves are further developed through a combination of the component fragility curves in the bridges. Comparisons of the fragility curves between the straight and skewed bridges indicate that the larger the skew angle, the more vulnerable the bridges, regardless of NSD bridges, bridges with SD columns, and retrofitted bridges. Formulas that consider effect of skew on the values of fragility parameters in the fragility curves are derived for each bridge class, component type, and limit state. Finally, the retrofit of columns and seismically designed columns can reduce column damage probabilities without significantly increasing demands to the other bridge component types, leading to a lower bridge system risk than that for the NSD bridges. However, although the other three retrofits (IB&KP, RC&SK, and SE&SK) can reduce transverse and/or longitudinal demands on the bearings, the column demands remain a similar or worse damage level than that for the NSD bridges, resulting in a similar or higher risk for the three retrofitted bridge systems.

1. Introduction

Skewed bridges are commonly used in highway intersections and interchanges where straight (unskewed) bridges are not appropriate. Over the past decades, the tendency for bridge decks to move along the skew direction has made these bridges more vulnerable to earthquake loads. Extensive damage to the columns with continuous connections to the superstructure as well as large in-plane offset of the deck near the abutment was observed in the short stiff skewed reinforced concrete box girder bridges during the 1971 San Fernando, the 1994 Northridge, and the 1995 Kobe earthquakes [1]. Several research efforts were made to investigate the behavior of this type of skewed bridge [2–4]. Skewed bridges with short and stiff columns tend to exhibit in-plane rigid body response. The impact between the deck and abutment causes rotation of a deck. If the columns are rigidly connected to the deck, extensive damage to the columns occurs because the effect of the deck rotation can induce large torsion in the column which has originally been subjected to bending [5]. Menassa et al. [6] investigated the effect of a skew angle on simple-span reinforced concrete slab bridges, but with a focus on design truck loads specified in the American Association for State Highway and Transportation Officials standard [7]. The results showed that the AASHTO Standard Specifications procedure gave similar results to the analytical maximum longitudinal bending moment for a skew

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Table 1
Dimensions of bridge models.

Bridge type		Bridge sample							
		1	2	3	4	5	6	7	8
MSSS concrete	Span length (m)	7.60	9.10	10.70	20.10	13.40	9.40	12.20	27.40
	Deck width (m)	8.20	7.50	12.60	8.60	10.40	9.20	18.60	6.60
	Column height (m)	4.43	3.34	3.74	4.00	4.23	6.01	6.06	3.88
MSC concrete	Span length (m)	39.60	22.60	18.90	21.00	26.20	10.40	14.50	15.20
	Deck width (m)	21.20	12.80	10.80	8.00	13.10	14.10	8.70	9.80
	Column height (m)	4.00	3.93	6.29	3.19	4.20	3.64	4.46	5.93
MSSS steel	Span length (m)	18.30	20.40	15.50	13.70	25.60	7.30	8.80	10.40
	Deck width (m)	8.70	8.00	4.90	10.50	29.70	5.50	7.40	12.80
	Column height (m)	5.10	3.62	5.95	4.02	3.54	3.90	4.26	6.62
MSC steel	Span length (m)	13.40	39.00	25.10	29.90	18.20	19.80	22.30	40.80
	Deck width (m)	13.00	12.90	10.20	14.50	20.10	5.50	10.30	7.90
	Column height (m)	3.72	3.49	3.93	5.42	4.20	5.76	4.08	6.74
SS concrete	Span length (m)	20.40	7.90	10.40	18.00	8.40	15.50	12.20	23.20
	Deck width (m)	9.50	7.70	6.20	7.30	9.00	13.20	8.40	6.90
SS steel	Span length (m)	9.40	20.80	14.90	7.90	39.90	24.40	12.50	6.60
	Deck width (m)	6.30	11.90	8.20	5.50	3.70	6.10	4.90	7.40

angle less than or equal to 20°. However, as the skew angle increased, AASHTO Standard Specifications procedure overestimated the maximum moment in the slab.

Lateral restraints (shear keys) on two sides of an elastomeric bearing are primary elements to limit excessive transverse movement and are in the form of a concrete shear block, rolled steel angles, or welded plates [8]. A slight gap between the elastomeric bearing and restraints is placed to allow longitudinal movements due to the temperature change. The study of the effect of shear keys on the seismic modeling of skewed simple-span slab-girder bridges with elastomeric bearings [9] indicated that ignoring the nonlinearity in the shear key model can result in erroneous prediction from finite element analysis of the skewed bridge.

Fragility curves are increasingly being used in probabilistic seismic risk assessment of highway bridges. Fragility curves, which are conditional probability statements of a bridge's vulnerability as a function of ground motion intensity, have been developed using expert opinion [10], empirical data from past earthquakes [11–13], and analytical methods [14,15]. Because both expert-based and empirically based fragility curves have some inherent limitations, analytical methods have been extensively studied, including spectral analysis [16], nonlinear static analysis [17,18], and nonlinear time history analysis [19,20].

In this study, analytical fragility curves are developed for six bridge types (multi-span simply supported (MSSS) concrete bridges, multi-span continuous (MSC) concrete bridges, MSSS steel bridges, MSC steel bridges, single span (SS) concrete bridges, and SS steel bridges) of skewed and straight bridges with three categories (non-seismically designed (NSD) bridges, bridges with seismically designed (SD) columns, and retrofitted bridges) common to the central and southeastern United States (CSEUS). Detailed three-dimensional nonlinear analytical models, which accounts for the nonlinear behavior of the columns, bearings, and abutments, are developed in the OpenSEES platform [21]. These models are used in conjunction with a suite of ground motions, which were developed for the region, to assess the seismic demands placed on each bridge component. Using a set of appropriate limit states, fragility curves are developed by considering multiple vulnerable bridge component types such as the columns, fixed bearings, expansion bearings, and abutments in both the longitudinal and transverse directions. The equations proposed for fragility parameters in the fragility curves account for the effect of skew and are developed for each limit state, component type and bridge type, which is useful for improving the accuracy of bridge damage and downtime using seismic loss assessment tools [22,23]. Finally, results from the SD and retrofitted bridges are compared with those from NSD bridges, and the effects of retrofit and skew angle on the bridge responses are investigated.

2. Numerical modeling of skewed bridges

In this study, three bridge categories: (1) non-seismically designed (NSD) bridges; (2) bridges with seismically designed (SD) columns; and (3) bridges retrofitted by (i) column jackets, (ii) isolation bearings and keeper plates, (iii) restrainer cables and shear keys, or (iv) seat extenders and shear keys, are taken into account. For each category, six bridge types common in the CSEUS are evaluated, including: (1) multi-span simply supported (MSSS) concrete girder; (2) multi-span continuous (MSC) concrete girder; (3) MSSS steel girder; (4) MSC steel girder; (5) single span (SS) concrete girder; and (6) SS steel girder bridges. Furthermore, in each bridge type, four cases of skew angles at 0°, 15°, 30°, and 45° are considered to investigate the skew effect. Typical details for these bridge types were collected from a study in which Choi [24] examined over 150 detailed sets of bridge plans from the CSEUS. The review of these bridge plans has shown that multi-column reinforced-concrete bents with 1% longitudinal reinforcement ratios in columns are the most typical construction type. The typical column for the steel and concrete girder bridges is circular with a diameter of 914 mm. The typical bent beams are 1067 mm wide by 1219 mm deep. The typical abutment is a pile-bent non-integral type. The concrete girder bridges utilize elastomeric pads for the bearings, while the steel girder bridges generally use steel fixed and rocker-type bearings. Nielson [25] and Nielson and DesRoches [26] analyzed basic geometric characteristics of each bridge type (straight bridges) in terms of span length, deck width, and column height. Eight representative configurations shown in Table 1 were generated for each bridge type. The numerical skewed bridge models established in this study are based on this previously obtained information. Each bridge type is assumed to have non-integral abutments and skewed angles ranging from zero to forty five degrees. The multi-span bridge types are assumed to have three spans (Fig. 1).

Based on the typical details taken from the examined bridge plans, 3-D numerical models are generated for all considered skewed bridge types and their respective configurations using the finite element platform OpenSEES. The superstructure of each