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Seismic vulnerability assessment of RC skew bridges subjected to mainshock-aftershock sequences

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A B S T R A C T

Due to the potential of strong aftershocks in the increase of vulnerability of bridges damaged under mainshocks, accurate evaluation of the structural performance during the seismic sequences is essential. This paper investigates the effect of different parameters such as skew angle of deck and direction of seismic excitation on the fragility curves of RC skew bridges subjected to mainshock and aftershocks. Fragility assessment is performed using a cloud analysis method subjected to a wide range of as-recorded sequences. First, a proper engineering demand parameter (EDP) which can result in the most probability of failure at bridges employed in this study is determined. The vulnerability of the bridge is then evaluated for different geometries representing various skew bridges and also for different incidence angles. Finally, comparisons are made with the fragilities in HAZUS. Results indicate that fragilities are significantly affected by aftershocks thus considering mainshock only is found to be unconservative. Comparison of median values for bridges with different skew angles across all damage states reveals that bridges with small skewness (almost straight geometry) can be less vulnerable than those with more skewness. Furthermore, fragilities are extremely sensitive to the direction of ground motion and therefore exclusive consideration of incidence angle can underestimate the seismic vulnerability in skew bridges. Results also show that the fragilities obtained based on aftershock and excitation orientation effects are more vulnerable than predicted by HAZUS and thus it seems necessary to revise damage functions for bridges in HAZUS in order to achieve a more accurate seismic risk assessment.

1. Introduction

Strong aftershocks occur in many regions where complex fault systems exist. When the first rupture takes place, all of the cumulative strains are not released. Therefore, high stresses form at different places causing sequential ruptures until the complete stabilization of the fault system [1]. For example, in the Wenchuan earthquake (2008) with a magnitude of 7.9 leading to collapse of and an increase in damage to structures damaged by the mainshock [2], about eight aftershocks with magnitudes of 6–6.5 were registered. The 1999 Kocaeli earthquake (M7.4) with an aftershock (M5.0), which happened approximately one month after the mainshock in Turkey, killed seven individuals, injured 239 people and collapsed dozens of buildings in three cities near the aftershock epicenter [3]. Under mainshock, the structural strength and stiffness of a structure is reduced. Due to limited time between the mainshock and aftershock, repair always becomes impossible, leading to damage increase or causing collapse [4,5]. Most studies focused only on mainshock effects, while analytical studies on the response of structures subjected to multiple earthquakes have shown that multiple earthquakes can increase damage level of structures relative to mainshock [6–11]. Nevertheless, most current seismic design codes have been presented based on the seismic vulnerability of structures under single earthquake, ignoring damage induced by strong aftershocks following a mainshock.

An important aspect of the seismic vulnerability of structures is to derive fragility curves to determine the damage level subjected to different earthquake intensities [12]. Some of recent studies have compared fragility of buildings under MS-AS sequences with MS-only, and have showed that multiple earthquakes can increase vulnerability of buildings and thus, neglecting aftershocks may lead to considerable underestimation of the seismic collapse risk [9,13–15 and 50]. However, most of the previous studies regarding multiple earthquake effects were focused on buildings, where seismic assessment of bridges in most of studies has been presented based on mainshock only [16–19]. Since highway bridges play a significant role in the economy of a country, an accurate evaluation of their collapse risk during seismic sequence loading is necessary. There has been limited research regarding aftershock effects on fragility of bridges. Results from these studies indicated that aftershocks can significantly increase the seismic vulnerability of highway bridges [20–23]. Despite development of the fragility curves for bridges in these studies, there are several significant shortcomings:

Past studies revealed that some irregular bridges such as skew bridges have the potential for significant damage in comparison with straight bridges under earthquake events [24–26]. Nevertheless, seismic vulnerability of skew bridges under MS-AS sequences has not been studied yet. On the other hand, damage level of bridges can be

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affected by the direction of seismic excitation. Some directions may develop different modes of failure in bridges which are not the same as the modes formed by conventional excitation along the longitudinal and the transverse deck axes. The effect of seismic incidence angle on fragility of bridges has been examined by a few researchers. For example Torbol and Shinozuka [27] derived fragility curves for regular and symmetric bridges and showed that longitudinal and transverse directions do not necessarily lead to the most critical response and thus if the angle of seismic excitation is not considered, damage level in bridges can be underestimated. Taskari and Sextos [28] investigated the sensitivity of the fragility of a straight bridge along the seismic incidence direction and indicated that this parameter may have a significant impact on the fragility of bridges. However, all the aforementioned studies are pertinent to straight bridges and did also not take into the effect of multiple earthquakes.

This paper aims to evaluate the fragility curves of skew bridges subjected to mainshocks and aftershocks using a cloud analysis method by considering various parameters. The first step in developing fragilities is to choose a proper engineering demand parameter (EDP). Two of the most common EDPs have been adopted in order to find the most critical EDP for the bridge classes considered in this study. Then, an analytical study has been performed to investigate the effect of skew angle on the seismic vulnerability of bridges. Four different angles from 20° to 80° are considered to derive fragility curves for both mainshock only (MS-only) and mainshock-aftershock (MS-AS) sequences. Next, seismic responses of skew bridges are investigated under different incidence angles to evaluate the sensitivity of fragility curves along the direction of ground motions. Finally, comparisons are made with the fragilities in HAZUS-MH [41] and the usability and efficiency of fragilities developed in HAZUS regarding effects of aftershock and excitation direction are discussed.

2. Description of a case study skew bridge

Painter Street Overpass (PSO) has been considered in this study. This bridge was built in the year 1976 and is located in the northwestern California. With a total length of approximately 81 m, this two-span RC bridge comprises a continuous reinforced concrete multi-cell box girder deck supported on two integral abutments at both ends. The bridge has a two-column bent (pier), and the skew angle of the bridge is about 39°. The height of columns is approximately 8 m with an octagonal cross-sectional geometry which is variable along the length of column and tapers from 2.7 m measured from the top of the column to 1.5 m at the base. This pier is consisted of 36 longitudinal bars, 35.8 mm-diameter (#11) and 12.7 mm-diameter (#4) transverse reinforcement in the form of spiral. Substructure system consists of 20 concrete friction piles of 0.3 m diameter. This bridge is typical of short-span bridges in California, spanning two or four-lane separated highways [29,30]. The cross section along a plan and elevation view of the bridge has been shown in Fig. 1.

Three-dimensional non-linear finite element models (FEM) are established in Open System for Earthquake Engineering Simulation (OpenSees) platform developed by PEER.

The RC deck has been modeled as an elastic beam column element; it is assumed that superstructure behaves elastically during the earthquake according to the assumption presented by the Caltrans Seismic Design Criteria [32]. The total weight of the deck is about 25 MN and masses at each node are calculated using the tributary area of the bridge. The abutment model consists of a zerolength element, which is defined by two nodes at the same location, associated with longitudinal, transverse, and vertical nonlinear responses of abutments. Rotation of both abutments are free around the x and y axes. Seismic sequences are applied in both the longitudinal and transverse directions, and the structural responses in terms of curvature ductility and transverse drift have been investigated. The pile foundations are modeled by use of translational and rotational springs with zerolength element. Spring stiffness values of the pile group have been calculated based on equations provided by Zhang and Markis [33].

A displacement-based beam-column element with a distributed plasticity along the element and five integration points was used to model the piers. This element is based on the displacement formulation and the integration along the element is based on Gauss-Legendre quadrature rule [31]. The column cross-section in finite element (FE) model was assumed to be a circle with diameter equal to total width of the original octagon section (i.e. 2.7 m in top and 1.5 m in base). The rigid link is used to connect two columns to the deck. They have been modeled using fiber cross-sections with two different characteristics for confined concrete (core) and unconfined concrete (cover) based on Concrete-06 material available in OpenSees to define the concrete properties, where nonlinear tension stiffening and compressive behavior are modeled based on Thorenfeldt curve. The material of steel bars in all structural models was considered of steel02 type in which uniaxial Giuffre-Menegotto-Pinto steel material with isotropic strain hardening is used [31].

Although these elements are able to accurately simulate the concrete cracking and steel yielding, they are incapable of modeling strength degradation such as bond slip and shear failure [54]. However, this degradation can be modeled using rotational springs and their stiffness can be obtained from the equation proposed by Elwood and Moehle and Moshref et al. as given below [54,55]:

$$K_{slip} = \frac{8u}{d_b f_s} EI_{flex} \tag{1}$$

where d_b is the nominal diameter of longitudinal bar, EI_{flex} is the effective flexural rigidity, u is the bond stress which is equal to $0.8\sqrt{f'_c}$ (MPa), f'_c is the compressive strength of concrete, and f_s is the stress in the longitudinal rebar which can be considered equal to yield stress f_y [55]. After modeling and analysis based on the above material models, an eigenvalue analysis was performed. Accordingly, the first and second modal frequencies mode were obtained as 1.43 Hz and 1.82 Hz, which is very close to the study done by Markis and Zhang [32].

2.1. Models

In this paper the effect of skew angle as well as seismic excitation angle on the fragility of skew bridges is investigated. In all models, the two horizontal components of the ground motions are applied. The role of skewness on the damage of bridges is studied for different angles, from 20° to 80°. The models for this parametric study are presented in Table 1. Skew angle has been shown in Fig. 1b. Model Angle6 is an original model of PSO in which skew angle is equal to 39 °, as mentioned in Section 2. Also Angle 8 (model 4) is close to a straight bridge (bent frame perpendicular to the deck).

Furthermore, in order to examine the effect of direction of seismic excitation on the vulnerability of skew bridges, seven incident angles are considered between 0° and 90°. It should be noted that according to the study by Torbol and Shinozuka, in asymmetric bridges, fragility curve varies as the excitation direction ranges from 0° to 360° [27]. Since this paper aims to show the consequences associated with ignoring the effect of direction of seismic excitation in vulnerability of bridges, incident angles is considered between 0° and 90° only. Table 2 lists the models for this part. The angles have been measured with respect to longitudinal axis of deck. It should be kept in mind that, first model (Excit-1) is the same as the model Angle6 in which the ground motions have been applied along the longitudinal and the transverse axes of bridge (i.e. 0° and 90°). Other models (Excit-2 to Excit-7) are stablished based on a counterclockwise rotation about the vertical bridge axes. Two horizontal accelerograms for each ground motion along the axes x′ and y′ represented as $\ddot{u}_{x'}$ and $\ddot{u}_{y'}$, respectively (Fig. 2) have been computed by using Eqs. (2) and (3):