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Deck rotation of straight bridges induced by asymmetric characteristics and effect of transverse diaphragms

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ABSTRACT

The 2010 Maule and 2015 Illapel earthquakes recently affected the highway infrastructure in Chile. Deck rotation in straight and skewed bridges, damage to the connection between the superstructure and substructure, and even collapse of bridges were observed in these events. However, deck rotation in straight bridges has been identified as an unusual failure mode. The main objective of this research is to evaluate if potential asymmetries in the bridge characteristics can be a probable reason that explain deck rotation observed in straight bridges. The second objective is to assess the effect of transverse diaphragms on the seismic behavior of these bridges. In order to achieve these objectives, the Chada underpass, which suffered deck rotation, damage to lateral stoppers and prestressed concrete girders during the Maule earthquake, is used as a case study. The asymmetries considered in this study are related to the variation of the strength of the lateral stoppers, the coefficient of friction of the elastomeric bearings, and the gap distance between the lateral stoppers and prestressed concrete girders. The induced asymmetries are evaluated with a three-dimensional model of the bridge developed in Opensees. The seismic response of the bridge is obtained from nonlinear dynamic analyses considering seven seismic records applying both horizontal components simultaneously. From the results of this study, it is concluded that the studied asymmetries induce deck rotations that can explain only part of the observed deck rotation in the studied straight bridge. A maximum relative horizontal displacement of the deck of 58.2 cm was estimated for the case with asymmetric strength of lateral stoppers, which is only 41% of the residual relative displacement measured in Chada bridge after the Maule earthquake. Additionally, it is concluded that the incorporation of transverse diaphragms, which is required by current Chilean bridge design code, improved the seismic behavior of the studied bridge.

1. Introduction

Two large earthquakes have affected the central region of Chile during the last decade. The 2010 Maule earthquake, with a moment magnitude of Mw = 8.8, affected the region from Arauco to Valparaíso and its epicenter was located 100 km northeast of Concepción [1]. The highway infrastructure was seriously affected by this earthquake, with estimated losses of US$850 million [2]. During this earthquake, the peak ground acceleration (PGA) reached 0.65 g at Concepción and between 0.17 and 0.56 g at Santiago [3].

The observed damage in bridges after the 2010 Maule earthquake has been reported by several authors [1–5]. The typical failure modes observed were damage to connections between superstructure and substructure, unseating of spans in skewed bridges due to in-plane rotation, and column damage due to permanent ground movement [3]. The unusual failures observed were unseating of spans in straight bridges due to in-plane rotation, web rupture of prestressed girders, and collapse of historic masonry bridges. From a study of 100 bridges, Shanack et al. [4] reported web rupture of prestressed beams due to the absence of diaphragms, span collapse due to the loss of stoppers, span collapse due to small seat width, and cracking at the welding notch of steel beams.

The 2015 Illapel earthquake had a moment magnitude of 8.3 and its epicenter was located 48 km west to Illapel in the Coquimbo region. As a consequence of this earthquake, eight bridges suffered damage, but their functionality was not affected [6]. The observed damages were displacement and rotation of the superstructure due to sliding of elastomeric bearings, settlement of embankments, and expansion joint damage due to the deck-abutment pounding [6].

Deck rotation in skewed bridges during severe ground shaking are

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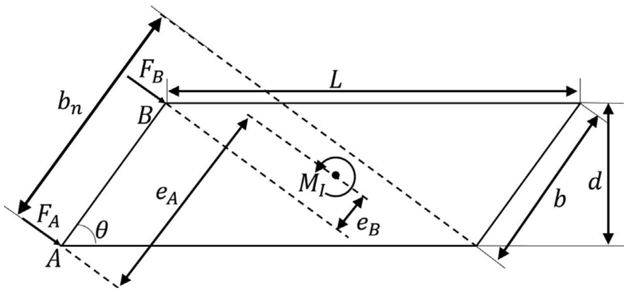

Fig. 1. Deck rotation due to impact forces in skewed bridges (Adapted from [1]).

induced by deck-abutment pounding and the incoherent response of the substructure [1]. Deck-abutment pounding generates a moment in the superstructure, caused by the impact force and its eccentricity with respect to the center of gravity (Fig. 1). The geometric conditions for a skewed bridge to rotate without contact with the abutment parapet wall is explained by Kawashima et al. [1].

The observed deck rotation in straight bridges in the 2010 Maule earthquake has been attributed to a greater excitation of the rotational mode in comparison to other modes in the absence of diaphragms. The rotational mode of vibration of straight bridges may have been sensitive to ground motions, and any accidental eccentricity between the center of mass and the center of rigidity of the superstructure could have produced substantial rotations [7]. The observed deck rotation might also have been generated by the deck-abutment pounding and the incoherent abutment response in the transverse direction [1]. In experimental tests, Shi and Dimitrakopoulos [8] have observed in-plane rotation of straight decks. To study this rotation, the authors proposed a mathematical method to analyze the relevance of the frictional coefficient between the deck and the abutments. The authors concluded that the frictional coefficient has an important influence on the deck rotation, but this parameter is difficult to study because its influence on the deck rotation is strongly nonlinear and hard to predict. Additionally, several authors have studied the seismic response of bridges considering deck-abutment pounding [9–14].

From the studies summarized above it can be concluded that there is still no clear explanation of the deck rotation in straight bridges nor of the influence of transverse diaphragms in this rotation. Therefore, the main objective of this research is to evaluate if potential asymmetries in the bridge characteristics can be a probable reason that explain deck rotation in straight bridges. The second objective is to assess the effect of incorporating transverse diaphragms in the deck rotation and seismic behavior of these bridges. The asymmetries considered in this study are related to the variations in the strength of the lateral stoppers, the coefficient of friction of the elastomeric bearings, and the gap distance between the lateral stoppers and the prestressed concrete beams.

In order to achieve the proposed objectives, the Chada underpass, a straight bridge that suffered deck rotation during the 2010 Maule earthquake [3] was chosen as the case study (Fig. 2). The deck rotation caused by the assumed asymmetric characteristics of the bridge are studied with nonlinear dynamic analyses (NDA) using seven seismic records applied simultaneously in both horizontal directions and with different intensity. The three-dimensional (3D) nonlinear model of the bridge was developed in Opensees software [15]. The model includes sliding of the elastomeric bearings, the nonlinear behavior of lateral stoppers, and the deck-abutment impact. For the rest of the superstructure and substructure a linear elastic behavior is assumed. From the results of the NDA, four displacements are evaluated to characterize the deck rotation, the seismic demand on lateral stoppers, the permanent transverse displacement of the deck, and the deck-abutment impact. Finally, the bridge model with added transverse diaphragms is evaluated to assess their influence on the seismic behavior of the Chada bridge. This latter analysis is of great relevance, since transverse diaphragms are mandatory in the current Chilean seismic design code [16].

2. Overview of typical bridge modeling

Several numerical models have been proposed to characterize the seismic behavior of bridges. Filipov et al. [17] developed a 3D model in Opensees to evaluate the concept of quasi-isolation in bridges of the state of Illinois in the US. Siqueira et al. [18] constructed fragility curves for Canadian bridges to assess the use of seismic isolators in the replacement of conventional elastomeric bearings. Kaviani et al. [19] studied the influence of the skew angle on the seismic behavior of box-girder bridges, and Seo et al. [20] analyzed the seismic response of curved bridges. All these authors constructed a 3D model in Opensees to develop their studies, where the superstructure was represented with linear elastic beam-column elements and transformed section properties. For the substructure, the authors considered the non-linear behavior of the columns using beam-column elements containing fiber sections. Additionally, Filipov et al. [17] simulated the columns embedded in the base to consider a rigid foundation on rock. Kaviani et al. [19] considered a rigid connection between the superstructure and substructure, shear keys in the abutments and a gap between the deck and the abutments. Finally, Seo et al. [20] modeled the soil-structure interaction with rigid, translational, and rotational springs.

Several researchers have also built numerical models of bridges to study how their seismic performance is affected by replacing conventional elastomeric bearings with alternative systems. Filipov et al. [17] studied three types of elastomeric bearings to evaluate a seismic quasi-isolation system. The authors simulated the bearings behavior with a coupled frictional model, which allows sliding in any direction on the horizontal plane. If this coupling is not considered, the displacements are underestimated and the forces generated in bearings are overestimated. The bidirectional constitutive model is able to capture the shear forces, the sliding and the plastic deformation of the elastomeric bearings. Li et al. [21] proposed a system for connecting the superstructure with the substructure based on elastomeric bearings that can slide together with X-shape metal dampers. For modeling such bearings, the authors used the Flat Slider Bearing Opensees element, which considers the frictional coefficient according to the Coulomb model. Siqueira et al. [18] considered seismic isolators to connect the superstructure with the substructure. These isolators were simulated with bilinear constitutive relationships in both horizontal directions,

Fig. 2. Case study, Chada underpass (repaired structure after the 2010 Maule earthquake).