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Analytical fragility curves for non-skewed highway bridges in Chile

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ABSTRACT

Recent earthquakes in Chile and worldwide have caused significant economic losses due to the damage on the road bridge network. To conduct seismic risk assessment studies and to improve resilience of bridges, seismic vulnerability studies are required. The main objective of this study is to construct fragility curves of typical non-skewed highway bridges in Chile. The fragility curves are obtained from an incremental dynamic analysis of a two-dimensional model of the bent cap of a two-span simply supported underpass. As most bridges are constructed with seismic tie-down bars, their constitutive behavior was obtained experimentally. A total of five seismic bar specimens were tested to characterize their cyclic behavior in bridges with and without transverse diaphragms. The incremental dynamic analysis was performed with the two horizontal components of seven seismic records obtained from the M_w 8.8, 2010 Chile earthquake. Additionally, a parametric study is conducted to assess the seismic behavior of bridges with different configurations of seismic bars, with lateral stoppers, and with varying length of the transverse seat width. Results from this study reveal that seismic bars have a limited contribution to the seismic performance of the studied bridge, especially when lateral stoppers are incorporated. Additionally, the transverse seat width is found to be critical to reduce the collapse probability of the superstructure. The provided fragility curves may be used for seismic risk assessment and to evaluate possible improvements in seismic bridge design codes.

1. Introduction

The road infrastructure has been affected by recent earthquakes in Chile (2010 and 2015), Japan (2011) and New Zealand (2011). In Chile, approximately 300 bridges were damaged by the moment magnitude $M_w = 8.8$ Maule earthquake in 2010, which include 20 bridges with collapsed spans [1]. In the 2015 Chile earthquake, about 7 bridges suffered minor damaged. Damaged bridges in 2010 earthquake represented less than 3% of the total inventory of the country [1], but the connectivity was affected and most of these bridges required repairs. Several authors [1–4] have described and analyzed the damage in bridges due to this earthquake and in general, they all agree in their diagnoses.

The most common failure in typical highway bridges during 2010 Chile earthquake was the connection damage between the substructure and the superstructure (Fig. 1a), caused by excessive displacement of the superstructure [1–4]. This type of failure is the most likely reason for the low incidence of column damage [1]. In skew bridges, unseating of spans was generated due to rotation of the superstructure, possibly caused by the impact between the abutment and the superstructure. However, tests conducted by Rollins and Jessee [5] suggest that passive resistance at the abutment-superstructure interface may be much less for skewed bridges than for non-skewed bridges. Damage in Chilean bridges was concentrated in lateral stoppers and prestressed concrete girders (Fig. 1b and c), and was attributed mainly to changes in bridge configurations during the last decades. Before the 90s, bridges were designed with transverse diaphragms, reinforced concrete lateral stoppers, and seismic tie-downs bars. These seismic bars are vertical steel rods that connect the slab of the bridge with the bearing table of the substructure, as can be observed in Las Mercedes underpass in Fig. 1c. With the arrival of concession during the 90s, the design of these three elements was modified or they were even eliminated in some bridges. The concessions are private companies that design, built, and maintain highway systems and are supervised by the Ministry of Public Works.

Fragility curves are an appropriate tool to evaluate the seismic vulnerability of structures and to estimate the probability of exceeding a certain damage level for a specific seismic ground

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(a) Typical highway bridge (b) Independecia overpass (c) Las Mercedes underpass

Fig. 1. Typical highway bridges in Chile and observed damage after the 2010 Maule earthquake.

shaking intensity. Nielson and DesRoches [6] and Pan et al. [7] developed fragility curves for bridges in the US, and Tavares et al. [8] and Siqueira et al. [9] for bridges in Canada. Fragility curves of structures can be estimated from field observations of damage after an earthquake or by analytical approaches. In the provided references, the fragility curves were estimated by analytical methods using nonlinear models of bridges. In this paper, fragility curves for Chilean bridges are also estimated by an analytical approach, specifically by conducting an incremental dynamic analysis.

The main objective of this study is to obtain fragility curves for typical non-skewed reinforced concrete bridges in Chile (Fig. 1a). The second objective is to quantify the effect of seismic bars, lateral stoppers, and length of the transverse seat width in the seismic behavior of such bridges. To quantify the contribution of seismic bars to the lateral response of bridges, an experimental program was conducted as part of this research. From the results of these tests, a constitutive model is proposed for the lateral response of seismic bars in bridges with and without transverse diaphragms. For the lateral stoppers, a nonlinear constitutive relationship based on a previous experimental program [10] is used.

Previous studies regarding the behavior of Chilean bridges during 2010 Maule earthquake called into question the contribution of seismic bars. Although these bars are designed for vertical forces to prevent the uplift of the deck [11], to some extent they provide lateral stiffness to the bridge deck when the lateral displacement of the superstructure is large, as can be observed in Fig. 1c. Yen et al. [4] doubt that the seismic bars provided vertical restraint during 2010 Maule earthquake because there was no evidence of vertical displacements in beams. Yashinsky et al. [12] postulated that the use of seismic bars had little impact on the seismic performance of bridges. However, both hypotheses contradict the study of Elnashai et al. [2], which concluded that seismic bars contributed to decrease the transverse displacement of the deck. In order to provide objective information to this discussion, the proposed experimental program of seismic bars seeks to quantify their contribution in the seismic behavior of bridges.

2. Experimental program of seismic bars

The definition of the seismic bars specimens, test setup, instrumentation, and load application protocol are described in this section. The tests are aimed at determining the contribution of the seismic bars in restraining the transverse displacement of the superstructure of bridges. Two specimens were tested to simulate the behavior of seismic bars in bridges with diaphragms (WD), and three specimens to simulate the behavior of bridges without diaphragms (WOD). The seismic bar specimens were subjected to cyclic lateral displacement and their characteristics are summarized in Table 1. In this table h_l corresponds to the clear distance of seismic bars from the bottom of the diaphragm or the slab, to the top of the bearing table, as shown in Fig. 2. The contribution of seismic bars in these two types of bridges are expected to be different, as the clear distance of seismic bars in bridges WD are smaller than that in bridges WOD.

Table 1
Test matrix.

Specimen	Loading Direction	h_l (cm)
WD1, WD2	In both directions	10
WOD1, WOD2	In both directions	72
WOD3	Only in one direction	72

2.1. Definition and design of specimens

To define the characteristics of the seismic bar specimens, a statistical analysis of the geometric characteristics of 13 highway bridges located in central Chile was conducted [13]. From this analysis, it was found that two seismic bars are installed between prestressed concrete girders at each side of the spans, and that the average diameter of these bars is 22 mm. The specified steel for these bars is A440-280H (f_y = 280 MPa), and the average clear distance (h_l in Fig. 2) is 200 mm and 1430 mm in bridges WD and WOD, respectively. The proposed specimens consist of a region of the bridge with two seismic bars between a pair of consecutive girders. Each specimen consists of three main elements: a reinforced concrete block at the bottom representing the bent cap or bearing table of the substructure; a reinforced concrete block on top representing the reinforced concrete diaphragm or slab, depending on the case; and two seismic bars connecting the bottom and top reinforced concrete blocks. Fig. 2 shows the tested regions of the bridges and the constructed specimens for specimens WD and WOD. In each specimen, two rollers were used to simulate the vertical displacement restraint provided by the elastomeric bearings.

For conducting the seismic bar tests, a 1:2 scale was selected due to laboratory limitations. Consequently, 16 mm was selected for the diameter of the seismic bars, and a clear distance (h_l in Fig. 2) of 100 mm was considered for specimens WD, and 720 mm for specimens WOD. The bent caps of the specimens were 2200 mm long, 400 mm high and 300 mm wide; the diaphragms were 1100 mm long, 740 mm high and 150 mm wide; and the slabs were 1800 mm long, 150 mm high and 300 mm wide. The seismic bars were anchored in the bent cap (bottom reinforced concrete block) with 90-degree hooks and the development length was enough to allow yielding of the bars [14]. At the top edge of the seismic bars a 90 mm long thread was manufactured. This thread was used to bolt the seismic bars to the top diaphragm or slab using a washer and two nuts, following construction practice. The diaphragms and slab were constructed with two cylindrical vertical perforations to allow the seismic bars to pass through