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Influence of the use of external shear keys on the seismic behavior of Chilean highway bridges

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A B S T R A C T

The present study evaluates the influence of external sacrificial shear keys on the seismic behavior of bridges commonly found in Chile. The damages observed in the external sacrificial shear keys as a result of the Maule earthquake of 2010 led to the revision of this type of elements. The results of a statistical analysis of Chilean highway bridges were used to identify a representative typology of bridges. Two models were used for the evaluation of the seismic behavior of the selected typology, given different soil conditions and seismic hazard zones, as follows: (1) one without sacrificial shear keys, which has no transverse displacement restriction and (2) other with non-linear shear keys, which offers transverse constraint to displacement up to a maximum deformation of the sacrificial shear key. Fragility curves were generated using non-linear analytical models and a series of compatible records.

The comparison of the fragility curves for damage levels I (initial slip) and II (large residual displacement of the superstructure) shows that the most vulnerable bridges are bridges without external shear keys, regardless of the seismic hazard zone and the type of soil. For damage level III (collapse) it is irrelevant whether or not the bridge has external shear keys.

1. Introduction

The observation of the main seismic events since late 20th century until today, as in Chile (1985, 2010, 2014), USA (1994), Mexico (1995, 2003, 2010), Japan (2001), China (2008), and Haiti (2010), has shown that highway bridges designed under latest design codes are structures vulnerable to failure or collapse; this has been attributed to conceptual problems in the normative design and the lack of attention during the development of design projects. A common fault detected in the performance of highway bridges with external sacrificial shear keys is the one associated with the diagonal tension phenomenon [1–6].

Several authors have theoretically and experimentally studied the seismic response of shear keys [7–13]. Buyukozturk et al. [7] performed tests to evaluate the shear strength and deformation behavior of prefabricated segmented bridge joints. They found that the strength of the epoxy joints was consistently larger than that of the dry joints, and proposed formulas to evaluate the shear strength of the joints. Kaneko et al. [8] proposed a simple design formula as a first step in the development of design aids for shear resistance of the shear keys and then validated their model based on fracture mechanics [9]. Megally et al. [10] carried out an experimental campaign to study the seismic response of interior and exterior shear keys. In addition, they developed analytical models to evaluate the capacity of the shear keys, as well as their post-peak performance under cyclical loads. Bozorgzadeh et al. [11] also conducted an experimental research program on external shear keys; unlike Megally et al. [10], they included the contribution of all the wall of the abutments. The results were used to develop an analytical model to estimate the lateral resistance of external and interior shear keys on abutments and cap beams. Also, recommendations for the detailing of the reinforcement of the external shear keys, as well as recommendations for their construction were made.

Goel and Chopra [12] investigated analytically the role of shear keys in the earthquake-resistant behavior of bridges located on geological faults. A simplified force–deformation model for the behavior of shear keys, based on the experimental results obtained by Megally et al. [10], was proposed. They concluded that the seismic demands on a bridge with non-linear shear keys on geological faults are limited by the demands of a bridge with elastic shear keys.

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Nailiang & Jianzhong [13] experimentally and analytically evaluated the seismic performance of highway bridges with different displacement control devices, including external shear keys. They proposed a simplified model for the hysteretic response of external shear keys with diagonal tension failure. The proposed model differs from the model proposed by Megally et al. [10] in that the stiffness associated with the unloading branches of the shear keys is equal to the initial loading stiffness of the element. Their results show that if the shear keys are well designed, the seismic demands of the piles can be effectively reduced, and the displacement of the elastomeric bearings can also be controlled to meet the performance objectives.

It is important to note that none of the previous investigations have assessed the variability of the seismic response of bridges with sacrificial external shear keys with the seismic hazard and the soil type.

In Chile, extensive damage has been observed in highway bridges due to great magnitude seismic events. In the 2010 Maule earthquake (Mw 8.8) approximately 300 bridges, representing about 3% of the total number of the existing bridges in the country [6], were damaged. The most frequent damages observed were: transverse displacement and/or excessive rotation of the superstructure, the collapse of segments of bridges due to the loss of vertical support in abutments or piles, damage associated to dynamic effects caused in skewed bridges or due to insufficient length in the supporting structures, damage in prestressed concrete beams due to the impact of the beam against the external shear key.

The objective of this research is to evaluate the influence of sacrificial external shear keys on the seismic behavior of highway bridges, considering different scenarios of analysis according to the soil type and hazard zone classification of the latest design code. In order to achieve the objective, the study of an intermediate pile of a typical Chilean bridge was carried out through the realization of a plane type model in OpenSees [14]. This model was elaborated by considering a typical structure obtained after a statistical analysis of the configuration of Chilean underpass and overpass highway bridges. A pushover analysis was conducted to determine the collapse characteristic; also, fragility curves were determined through an Incremental Dynamic Analysis (IDA) to establish the bridge performance and differences between considering or not the use of external shear keys. The model takes into account the non-linear behavior of sacrificial external shear keys, seismic bars, and elastomeric bearings.

Regarding the characterization of the seismic demand, 42 accelerograms obtained from the Maule earthquake (Mw = 8.8, 2010), and 47 from the Algarrobo earthquake (Mw = 8.0, 1985) were used to define the expected seismic hazard as established by Riddell [15], for the soil type classifications I, II, and III (according to the Chilean Seismic Code [16]), modified by extending indefinitely the zone of velocity amplification; for the elaboration of the fragility curves accelerograms compatible with each hazard level were calculated.

2. Typology of highway bridges in Chile

According to the statistical study carried out in this research, the most used bridge type in Chile consists of a reinforced concrete deck, continuous or simply supported (with an average span of 26.0 m between supports in typical bridges), on prestressed concrete beams (with an average of 4 beams), supported on abutments and/or piles composed of a cap beam and simple or multiple columns. Additionally, elastomeric bearings are placed under each beam, constituting the interface between the beams and the intermediate abutments and/or piles. Sacrificial shear keys are used in piles and abutments (Fig. 1). The purpose of the outer sacrificial shear keys is to restrict the transverse movement of the superstructure under extreme lateral displacement demands, preventing the superstructure from losing its vertical support and collapse [17–19]. A typical detail of sacrificial external shear keys is shown in Fig. 2 on a cap beam in the pile of a bridge.

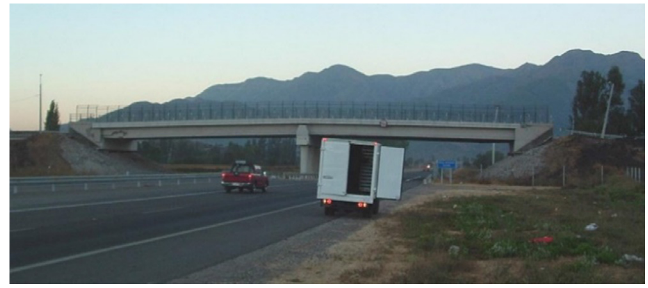

Fig. 1. Typical highway bridge in Chile.

External shear keys with an appropriate design must be able to restrict the lateral displacement of the superstructure in the case of extreme seismic events, acting as sacrificial elements in which the damage is concentrated, avoiding damage to the infrastructure (cap beams, columns, piles, and abutments).

For example, to ensure that external shear keys function properly as sacrificial elements, CALTRANS [18] states that the lateral load-bearing capacity of the shear keys must not exceed the greatest of 30% of the vertical reaction in the abutments and/or pile and 75% of the lateral capacity of the pile.

2.1. Damage observed on highway bridges after the Maule earthquake (2010, Mw 8.8)

Among the most frequently observed damage caused by the Maule earthquake was the sliding of the superstructure beams and support elastomers (Fig. 3a). In some cases, the superstructure collapsed as the result of excessive lateral displacement (Fig. 3b). Another type of damage frequently observed was that some sacrificial external shear keys presented shear failure of diagonal tension-type, as shown in Fig. 4. In all the observed cases of ductile behavior of the sacrificial external shear keys, excessive lateral displacements were avoided, without loss of the vertical support of the superstructure and no damage in the abutments and intermediate piles. It is important to mention that, although these external shear keys acted as sacrificial elements, such is the desired behavior for this type of elements.

2.2. Changes in seismic-resistant design criteria of Chilean highway bridges, following the Maule earthquake (2010, Mw 8.8)

Due to the damages observed in the Maule earthquake, MOP [19] modified the criteria for the earthquake resistant design of

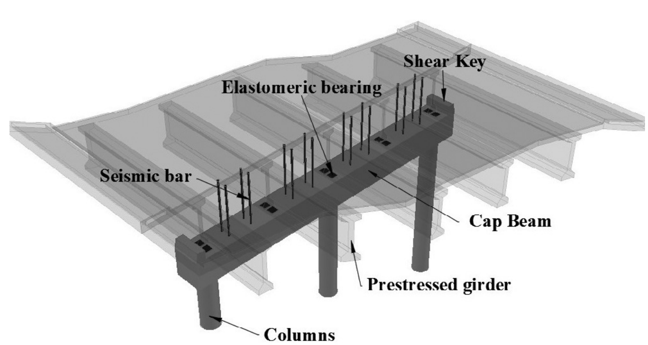

Fig. 2. Scheme of external shear keys in a bridge.