Soil Dynamics and Earthquake Engineering 112 (2018) 185–197

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Effect of exterior concrete shear keys on the seismic performance of laminated rubber bearing-supported highway bridges in China

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ARTICLE INFO

Keywords:
Exterior concrete shear keys
Laminated rubber bearings
Highway bridge
Parametric study
Coupling influence

ABSTRACT

Typical small to medium-span highway bridges in China are commonly equipped with laminated rubber bearings to accommodate superstructure movements from service-level loadings, and exterior concrete shear keys to restrain earthquake-induced superstructure displacements in the transverse direction. However, the past 2008 Wenchuan earthquake just highlighted the roles of bearings and shear keys in the performance of highway bridges. The bearing sliding as well as shear keys failure were typically observed during the earthquake, which resulted in excessive superstructure displacements and even catastrophic span collapse. The objective of this study is to investigate the effect of shear keys on the performance of laminated rubber bearing-supported bridges in China, with emphasis on the coupling between the shear keys and bearings. Nonlinear numerical models of bearing sliding and shear key failure are utilized and implemented in the finite element model of the global bridge. Incremental dynamic analyses are carried out to evaluate damage and failure process of the prototype bridge, followed by extensive parametric studies on the influences of shear key parameters. Results indicate that the shear keys designed with conventional practices are relatively ineffective in improving the bridge performance under large earthquakes. It is also concluded that the shear key parameters usually have coupling influences, which should be selected as a combination to achieve an optimal performance. Also, the shear key and bearing as a parallel system should be properly designed such that they can reach their peak forces simultaneously, providing an efficient resistance for the bridge superstructure.

1. Introduction

Small to medium span highway bridges constitute a large portion of the transportation systems in China. Some of the most distinctive design practices for these bridges include: (1) economical laminated rubber bearings are widely used without connections designed between bearings and bridge superstructure or substructure, which means that there is only friction resistance provided on the contact surface; (2) bearings are placed directly between superstructure and substructure through the embedded steel plates and concrete pads respectively, producing a rubber-to-steel interface at the top and a rubber-to-concrete interface at the bottom; (3) exterior concrete shear keys are always implemented at both sides of piers or abutments in the transverse direction to provide lateral restraint for superstructure.

When it comes to the concrete shear keys, there has been a controversial issue associated with their role in seismic behavior of bridges. For the past decades in China, concrete shear keys have been regarded as the secondary earthquake-resistant components, which are usually designed without any guidance from codes or specifications. For simplicity, they are generally treated as either sacrificial elements which are not considered in the dynamic analysis, or rigid restrainers having a large elastic stiffness. In this regard, seismic design of these laminated rubber bearing-supported bridges is mainly concentrated on the plastic hinging mechanism of substructure and its detailing. This presupposed earthquake-resistant mechanism is, however, difficult to achieve during an earthquake when the shear keys are designed without ensuring a reliable strength, as evidenced in the 2008 Wenchuan earthquake. Damage investigation [1–3] after the earthquake just demonstrated the deficiencies of superstructure-to-substructure connections for such bridges. The laminated-rubber bearings were severely damaged with bearings sliding off their original positions, whereas the concrete shear keys suffered from cracking or even total failure due to the pounding force from superstructure. Fig. 1 shows typical damages of exterior concrete shear keys in Wenchuan earthquake, which were characterized by significant diagonal cracks developed between shear keys and bridge substructures. Such kind of failure mode, which was called diagonal shear failure, was common for exterior shear keys with conventional design details in China, as verified

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https://doi.org/10.1016/j.soildyn.2018.04.033
Received 31 January 2018; Received in revised form 20 April 2018; Accepted 21 April 2018

Fig. 1. Typical shear key damages during the Wenchuan earthquake (diagonal shear failure).

by the post-earthquake damage investigation [1] and subsequent experimental works [4]. Both the bearing sliding and shear key failure contributed to the excessive superstructure displacements, especially in the transverse direction, considerably increasing the risks of unseating or span collapse. On the other hand, however, the substructure for most of the inspected bridges was found to be damage-free or experience minor damage, instead of forming plastic hinges in bridge piers. This phenomenon was unexpected yet illuminating. The bearing sliding and shear key failure could actually act as fuses, limiting the transmitted inertia force of superstructure and thus protecting substructure from excessive seismic damage. Nevertheless, the reduction in substructure seismic demands was achieved at the expense of an increase in superstructure displacements. After the earthquake, large amounts of bridges were severely displaced and several spans of superstructure even fell off the supporting substructures.

The seismic performance of concrete shear keys has been extensively studied experimentally and numerically. Megally et al. [5] carried out experimental studies on the failure modes of external shear keys at bridge abutments under earthquake loads. Three types of failure modes for shear keys, namely diagonal shear failure, flexural failure and sliding shear failure were identified for different shear key configurations, where the sliding shear failure was the most desirable for achieving a sacrificial response. Bozorgzadeh et al. [6] further developed a mechanism model for capacity evaluation of shear keys with sliding shear failure. These experimental works were then formatted and adopted by the latest version of CALTRANS guidelines (CALTRANS 1.7) [7], in which the design strength and reinforcement detailing for non-sacrificial and sacrificial shear keys were recommended. Xu [4] selected conventional shear keys that are widely used in China as the prototype and performed a series of quasi-static tests on them. The test results showed that the shear keys with conventional detailing tended to display a diagonal shear failure under increased imposed loadings. The seismic performance of typical shear keys in China was also experimentally studied by Han et al. [8] with emphasis on the influence of reinforcement ratios and joint types. This research eventually helped in developing different analytical models to predict the force-displacement responses of exterior shear keys with different failure modes. Geol and Chopra [9] investigated the role of abutment shear keys in the seismic response of ordinary bridges subjected to spatially-uniform and spatially-varying ground motions, and they found that the modelling assumptions on shear keys would generate significant impacts on the estimation of seismic demands in bridges. Bi and Hao [10] developed a detailed 3-dimensional finite element model to capture the shear key responses especially the pounding between shear keys and bridge decks. The numerical results indicated that the restraining effect posed by shear keys would complicate the torsional-lateral response of decks under bi-directional ground motions and neglecting the engagement of shear keys might lead to an inaccurate prediction of bridge seismic demands. Están et al. [11] evaluated the influence of external sacrificial shear keys on the seismic behavior of Chilean highway bridges, which concluded that the most vulnerable bridges were those without external shear keys, regardless of the seismic hazards and soil types. Li et al. [12] performed large-scale shake table tests on laminated rubber bearing-supported bridges with concrete shear keys, and the experimental results revealed that the shear keys could act as fusing components, restraining the bearing displacements while controlling the seismic demands in substructures. Numerical simulations were also conducted as a comparison with experimental studies. Good correlation between these two were achieved, validating the appropriateness of modelling assumptions in shear keys.

The scope of this study is limited to laminated rubber bearing-supported highway bridges that are widely used in China. By allowing the sliding of laminated rubber bearings, the influence of concrete shear keys on seismic response of bridges is numerically investigated in this study. The nonlinear behaviors of bearings, shear keys and bridge piers are well incorporated into the finite element model. Incremental dynamic analyses are first conducted to evaluate the sequence of damage for bridges with conventional design practices. Further, the influence of different shear key parameters on the individual component response as well as the global bridge performance is highlighted. It should be noted that only transverse seismic response of bridges is considered in the current study, as concrete shear keys are usually engaged in an earthquake in the transverse direction.

2. Overview of bridge modelling

2.1. Basic bridge prototype

This research utilizes a representative multi-span simply supported highway bridge in China as a prototype for illustration (see Fig. 2 for a basic configuration of this bridge). The prototype bridge is characterized as precast reinforced concrete T-girder superstructure that is supported on the reinforced concrete double-column pier substructure. The bridge superstructure has an equal span length of 25 m, which is one of the most commonly-used lengths in Chinese bridges. The clear height of pier bents is 8 m, and the column diameter is 1.4 m. The longitudinal reinforcement ratio of the column is 2.0%, with 38 mm-diameter steel bars circularly arranged in the column. Each T-girder is supported on two laminated rubber bearings at both ends, and in total there are ten bearings implemented at each bridge bent. The laminated rubber bearing has a diameter of 400 mm and a total height of 84 mm (60 mm high in rubber). Concrete shear keys are installed at both sides of the cap beam as exterior restraining devices. The shear key has an overall dimension of $500 \times 300 \times 1600$ mm in height, transverse length and longitudinal length respectively. Principle reinforcements in the shear key are composed of shear bars crossing the interface between shear key and cap beam, horizontal tensile bars distributed at top of cap beam and side bars spread along the sides of cap beam, as illustrated in Fig. 2. The initial gap between the shear key and superstructure is so small that it is not considered for this prototype bridge.