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Shake table studies of a highway bridge model by allowing the sliding of laminated-rubber bearings with and without restraining devices

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ABSTRACT

One of the most significant damages for highway bridges during the 2008 Wenchuan earthquake was the sliding of laminated-rubber bearings. The bearing sliding during the earthquake caused excessive superstructure displacement, which subsequently led to the failure of concrete shear keys, damages of abutments and expansion joints, and even span collapse. The main objective of this study is to experimentally investigate the seismic performance of highway bridges considering the sliding of laminated-rubber bearings. Three transverse restraining systems, namely without restraining devices, with concrete shear keys and with yielding steel dampers were tested on the shake table. Test results validate that seismic forces transmitted from superstructure to substructure can be substantially reduced by allowing the bearing sliding. However, if no restraining devices are implemented, the maximum, as well as residual bearing displacements, will be excessively large, making the superstructure-to-substructure connections the most vulnerable components. As restraining devices, yielding steel dampers are more effective than concrete shear keys by withstanding larger earthquakes and dissipating more energy. The tested model equipped with steel dampers can achieve a reasonable balance between bearing displacements and substructure seismic demands. Further, the experimental results are captured and justified by the supplemental numerical simulations.

1. Introduction

Highway bridges, especially those small to medium-span ones, constitute a large portion of global infrastructure systems [1–5]. In addition to regular passenger and freight transportation, a highway bridge also plays a critical role in providing necessary routes for disaster rescue, firefighting, and medical services in an emergency. Past earthquakes, including the 1994 Northridge earthquake [6], the 1995 Kobe earthquake [7], the 1999 Chi-Chi earthquake [8], the 2008 Wenchuan earthquake [9] and the 2010 Chile earthquake [10] demonstrated that bridges were highly vulnerable to earthquakes, whose collapse might cut off the trunk roads and hinder the post-earthquake rescue.

Economical laminated-rubber bearings [11] featuring alternate layers of rubber and steel sheets have been extensively adopted in highway bridges. The bearings possess the capacities of sustaining large vertical loads and accommodating thermal movements of the superstructure with low maintenance. For the convenience of construction, laminated-rubber bearings are usually treated as unrestrained bearings that can be directly placed between the superstructure and substructure without restraints except for friction resistance on the contact surface [12,13]. Another major benefit of not restraining laminated-rubber bearings is that the cavitation problems can be avoided, as mentioned in Tubaldi et al. [14]. It has been reported [15] that China has more than 800,000 as-built highway bridges, a large majority of which are equipped with unrestrained laminated-rubber bearings. The common practice in China is that the bearings are first placed on the concrete pads at the top of the substructure, and then superstructure rests on the bearings through several embedded steel plates. Thus, in this case, only friction will be induced on either top or bottom surfaces of bearings to provide lateral resistance for the superstructure. On the other hand, conventional concrete shear keys are normally installed on both sides of piers or abutments as transverse restraining devices to prevent excessive displacements under earthquake loadings [16]. However, concrete shear keys are commonly designed empirically in China without design guidelines available, as they have been for a long period regarded as the secondary earthquake-resistant components.

The performance of highway bridges with unrestrained laminated-rubber bearings and concrete shear keys has been examined by some previous earthquakes, including the 1999 Chi-Chi earthquake and the

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2008 Wenchuan earthquake. Reconnaissance report from the Wenchuan earthquake [17,18] demonstrated that the sliding of laminated-rubber bearings and shear key failure were mostly observed. The bearing sliding would initiate as soon as the friction resistance at the interface was exceeded. Such phenomenon could be further aggravated if the shear keys were not designed strong enough to restrain the bearing sliding displacements. Numerous shear keys were observed to be severely cracked or even sheared off during the earthquake. On the other hand, the bearing sliding could exacerbate the pounding between the superstructure and shear keys, which accelerated the shear key failure. Both the bearing sliding and shear key failure would largely increase the risks of unseating or span collapse. Most of the bridge substructure, however, unexpectedly survived after the earthquake with merely slight damages. This might be owing to the sacrificial characteristics of bearing sliding and shear key failure, which could effectively limit the inertia force transmitted to the substructure. Similar damages for highway bridges were also observed in the 1999 Chi-Chi earthquake, where the most common damage appeared to be the excessive superstructure displacement due to the sacrifices of rubber bearings and shear keys. The bridge piers in Chi-Chi earthquake only suffered from minor and repairable damages [19]. The 2010 Chile earthquake also revealed the bridge damages associated with the sliding of unrestrained laminated-rubber bearings when anchors and stoppers were eliminated between the superstructure and substructure due to construction congestion.

Since an unrestrained rubber bearing has the potential to provide an economic solution for highway bridges with isolation by initiating its sliding during an earthquake, extensive studies have been conducted to investigate its sliding response. Konstantinidis et al. [20] performed experimental studies on the seismic response of unrestrained laminated-rubber bearings on concrete surfaces, which concluded that the bearing could sustain a shear strain of 150–225% without sliding and display a maximum frictional coefficient of 0.53. Steelman et al. [21] also experimentally investigated the shear and friction response of rubber bearings on the concrete substructure. They found that the bearings exhibited approximately linear elastic response before sliding with a maximum shear strain of 125–250% and sliding response with a frictional coefficient of 0.25–0.5 depending on different combinations of roughness, applied load and velocity. The experimental findings from Steelman et al. [21] finally contributed to the development of a refined bearing sliding model, which was implemented in some numerical studies [22–24]. Similar experimental testing was also found in Xiang et al. [25], except that the bearings were placed in direct contact with steel plates, representing the common practice in China. The test results facilitated developing an improved bearing sliding model, which could capture the effect of sliding velocity and normal pressure.

Nevertheless, there are several limitations inherent in the above-mentioned studies. The experiments on bearing sliding were quasi-static, focusing on the local bearings without incorporating other bridge components like superstructure, substructure or restraining devices. Although the numerical studies were conducted on the overall bridge systems, the simplified bearing model used in the analyses might be inadequate to reflect the realistic bearing sliding behavior and its effect on global bridge response. To overcome these limitations, shake table test on global bridge systems should be conducted. This study utilizes large-scale shake table testing to investigate the performance of highway bridges by allowing the sliding of laminated-rubber bearings. In this regard, a quarter-scale simply-supported bridge model representative of typical bridge configurations in China was designed, built and tested on the shake table. Three different restraining systems, namely without any devices, with concrete shear keys and with yielding steel dampers, were considered in the current test. Supplemental numerical simulations on the tested model were also conducted to validate the experimental results.

2. Design of tested bridge model

2.1. Prototype bridge and tested model

Simply-supported highway bridges with continuous deck have been popular in China, as they do not require complex design process and can be constructed easily and rapidly. In this study, a non-skew, multi-span simply-supported highway bridge with a uniform span length of 25 m was chosen as the prototype. A single span of bridge superstructure consists of five RC T-girders whose total weight is 568 tons plus the dead-loads from non-structural components (e.g. deck pavements, guardrails). The substructure is composed of RC double-column piers on extended pile foundations. All the pier columns have identical dimensions, with a clear height of 8.0 m and a diameter of 1.4 m. The longitudinal steel reinforcement ratio of columns is 2.0% and the transverse volumetric steel ratio is 0.6%. Each girder is supported on two laminated-rubber bearings at both ends in the longitudinal direction, and there are in total ten bearings used at each pier. The bearing is circular in plan with a diameter of 400 mm and an effective height of 60 mm. Concrete shear keys are constructed at both ends of the cap beams in the transverse direction. The shear keys have a longitudinal length of 1.6 m that is equal to the width of the cap beams. They are cast monolithically with the cap beams with some reinforcing bars crossing the interface between the two, ensuring a sufficient shear key capacity. The initial gap between the superstructure and shear keys is 2 cm, which is set mainly for the convenience of construction. Fig. 1 shows the design details of the prototype bridge, including the elevation and transverse views, installation details of bearings, and steel reinforcement in shear keys and cap beams.

As the prototype bridge is a simply-supported structure with identical spans and pier bents, the transverse seismic responses for all the pier bents will be basically the same. Thus, a portion of the prototype bridge comprised of a whole span, two half side spans, and two pier bents, was selected to design the tested model for simplicity, as enclosed by the dashed lines in Fig. 1. The selected structure was able to display a similar transverse seismic response as the prototype due to the structural symmetry.

Fig. 2 shows the quarter-scaled bridge model used in the shake table testing, which is a single-span structure with two identical pier bents. The mass of the two half side spans is lumped on this tested span. In the model, rigid steel plates with iron blocks were used to model the bridge superstructure. The flexural and torsional stiffnesses of the superstructure were not accurately simulated as per the scale factors, as they usually had negligible influences on the overall seismic response of a simply-supported structure compared with the superstructure mass. Due to the large in-plane stiffness, the superstructure would move like a rigid body when subjected to transverse earthquake excitations. The scaled mass of the superstructure was calculated as 71 tons, which was 1/16 of the prototype mass (568 tons). To provide the required scaled mass, two steel plates each weighing 11.5 tons, and 24 iron blocks each weighing 2.0 tons were assembled together. As a main earthquake-resisting component, the model substructure should be properly designed to ensure that its capacities (e.g., flexural, shear, axial) could match well with the prototype values. For this purpose, the dimensions, as well as the steel reinforcements of the cap beams and columns, were designed as per the corresponding scale factors. The resultant longitudinal reinforcement in the pier columns consisted of 13 reinforcing bars with a diameter of 14 mm, which were circle-wise distributed around the central axis of the columns, as shown in Fig. 2. The steel reinforcement used in the model has a specified yield strength of 400 MPa, and the specified concrete compressive strength was 40 MPa. Testing of materials showed that the actual average yield strength for the steel reinforcement was 465 MPa, and the compressive strength of the concrete at the time of testing was 49 MPa, both of which were relatively larger than the specified values.