Soil Dynamics and Earthquake Engineering 86 (2016) 55–70

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Shake-table tests and numerical simulation of an innovative isolation system for highway bridges

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A R T I C L E I N F O

Article history:
Received 21 November 2015
Received in revised form
26 April 2016
Accepted 2 May 2016
Available online 6 May 2016

Keywords:
Wenchuan earthquake
Innovative isolation system
Laminated-rubber bearing
X-Shaped steel damper
Shake-table tests
Two-span bridge model

A B S T R A C T

Damage investigation of small to medium-span highway bridges in Wenchuan earthquake revealed that typical damage of these bridges included: sliding between laminated-rubber bearings and bridge girders, concrete shear keys failure, excessive girder displacements and even span collapse. However, the bearing sliding could actually act as a seismic isolation for piers, and hence, damage to piers for these bridges was minor during the earthquake. Based on this concept, an innovative solation system for highway bridges with laminated-rubber bearings is developed. The system is comprised of typical laminated-rubber bearings and steel dampers. Bearing sliding is allowed during an earthquake to limit the seismic forces transmitting to piers, and steel dampers are applied to restrict the bearing displacements through hysteretic energy dissipation. As a major part of this research, a quarter-scale, two-span bridge model was constructed and tested on the shake tables to evaluate the performance of this isolation system. The bridge model was subjected to a Northridge and an artificial ground motion in transverse direction. Moreover, numerical analyses were conducted to investigate the seismic performance of the bridge model. Besides the test bridge model, a benchmark model with the superstructure fixed to the substructure in transverse direction was also included in the numerical analyses. Both the experimental and the numerical results showed high effectiveness of this proposed isolation system in the bridge model. The system was found to effectively control the pier-girder relative displacements, and simultaneously, protect the piers from severe damage. Numerical analyses also validated that the existing finite element methods are adequate to estimate the seismic response of bridges with this isolation system.

1. Introduction

Small to medium-span highway bridges in China are commonly installed with economical laminated-rubber bearings that allow for thermal movement of the superstructure. The bearings are usually placed directly between the bridge girder and the pier, with no restraint of horizontal motion other than friction (Fig. 1). Furthermore, concrete shear keys, which are used as unseating-prevention devices in transverse direction, are expected to prevent excessive girder displacements from service-level and earthquake loadings. Typical damages [1–5] of small to medium-span highway bridges in the 2008 Wenchuan earthquake included: shear keys failure (Fig. 2(a)), sliding between laminated-rubber bearings and bridge girder (defined as 'bearing sliding', shown in Fig. 2(b)), abutment and expansion joints failure, and even span collapse (Fig. 2(c)). Investigations also revealed that for bridges suffering from bearing sliding, damage to piers and foundations was minor. Similar phenomena were also found during the 1999 Chi-Chi earthquake [6–8]. Lessons learned from the past earthquakes indicate: (1) bearing sliding is a common phenomenon during these earthquakes, and it can provide seismic isolation for the substructure, (2) the unseating prevention devices should be properly designed to control the pier-girder relative displacements.

In fact, some researches started to focus on the sliding effect of laminated-rubber bearings for small to medium-span bridges. AASHTO [9] has specified a so-called 'Fusing' design methodology for highway bridges. In this methodology, the connecting components between the superstructure and the substructure, such as rubber bearings, or some energy-dissipation devices can perform as fuses to mitigate the seismic demands of substructures. Analytical study conducted by Lu et. al [10] finds that the bearing sliding occurred in ChiChi earthquake plays an important role in limiting the seismic forces transmitting to pier columns. Liu et. al

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http://dx.doi.org/10.1016/j.soildyn.2016.05.002
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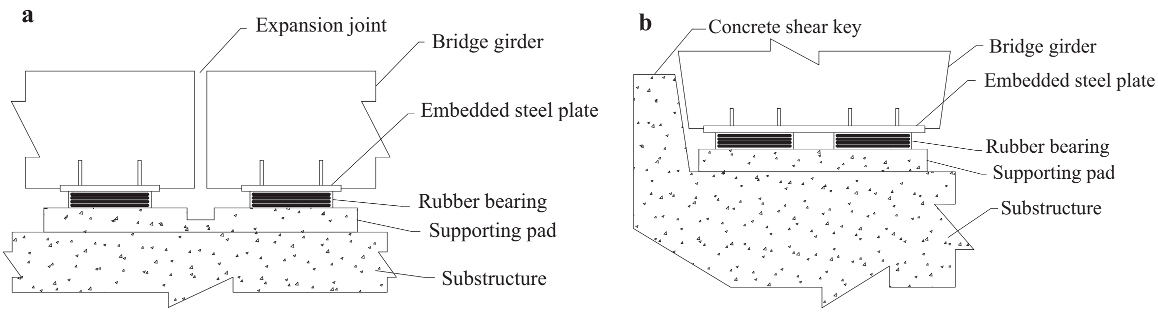

Fig. 1. Typical arrangement of laminated-rubber bearings on highway bridges: (a) longitudinal, (b) transverse.

Fig. 2. Typical damages of highway bridges during Wenchuan earthquake: (a) shear key failure, (b) bearing sliding, and (c) span collapse.

[11] adopt a friction-pendulum model in the dynamic analysis to approximately model the sliding behavior of laminated-rubber bearings. In Illinois of USA, experimental and numerical works [12–17] are carried out to investigate the sliding effect of rubber bearing and its application in typical bridges in Illinois. It is concluded that the typical rubber bearings of Illinois bridges can be designed and detailed such that they slide, to limit forces transmitted from the superstructure to the substructure, while accommodating the associated displacements. The previous studies, however, are only limited to numerical analyses or tests on local bearing components. No shake-table tests on a whole bridge system have been reported in the literature.

In this study, an innovative isolation system for small to medium-span highway bridges with economic laminated-rubber bearings is developed. The basic concept of the system is that the bearing sliding acts as isolation to cap or limit the force demands of piers, while an X-shaped steel damper is adopted along with the bearings to control the pier-girder relative displacements. The proposed isolation system does not require a complex design process and high cost of construction, in comparison with the conventional isolation system which might have some expensive devices, such as lead-rubber bearings or friction pendulum bearings required to be designed and detailed [18–21].

To investigate the seismic performance of this proposed isolation system, shake-table tests were conducted on a 12 m long, quarter-scale, two-span bridge model at Tongji Unversity, China. The model was designed and constructed based on the typical configurations and details of a simply-supported box girder bridge in China. Two bridge systems were tested: (1) without damper-only laminated-rubber bearings provide support for the bridge superstructure; (2) with damper-that is the proposed isolation system where X-shaped steel dampers are installed along with the bearings. The model was subjected to a series of gradually increasing ground motions in transverse direction. Furthermore, numerical analyses of the test model and a benchmark model were also conducted to provide supplements for the shake tests.

2. Innovative isolation system

AASHTO [9] has specified a global seismic design strategy for highway bridges, where the superstructure and the substructure remain essentially elastic and a fusing mechanism is provided at the interface between the two. According to the 'fusing' design strategy specified in AASHTO and lessons learned from the Wenchuan earthquake, an innovative isolation system for small to medium-span highway bridges in transverse direction is proposed and studied. The system (Fig. 3) mainly contains two parts: the laminated-rubber bearing and the X-shaped steel damper, which have been previously investigated through experimental tests. The proposed isolation system is actually a combination of seismic isolation and energy dissipation specified in AASHTO. Some characteristics of this system are observed as follows:

(1) The laminated-rubber bearing intended to transfer gravity load, is prone to slide along the bridge girder during an earthquake. The bearing sliding can actually act as seismic isolation, limiting the inertial forces transmitting to the substructure.
(2) As one type of energy-dissipation devices, X-shaped steel damper can provide the bridge with stable lateral resistance and dissipate substantial earthquake energy. The transverse displacements of the bridge girder will be greatly controlled

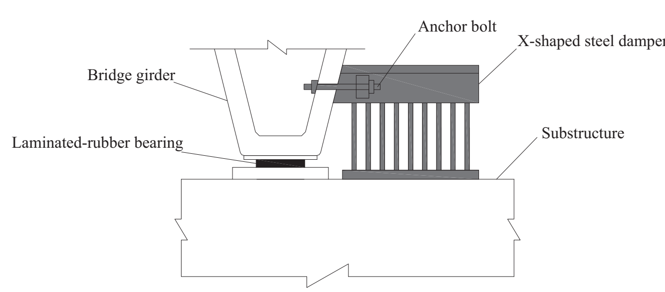

Fig. 3. Configuration of the innovative isolation system.