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Experimental and numerical study on seismic sliding mechanism of laminated-rubber bearings

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ABSTRACT

Typical laminated rubber bearings are widely used in small to medium-span highway bridges in China. These bearings are economical, and are proved to perform well at service-level conditions. However, damage investigation after the 2008 Wenchuan earthquake revealed that sliding between the laminated rubber bearing and the bridge girder was a common phenomenon, which could actually act as fuses and protect the substructures from severe damage. Thus no damage or only minor damage of substructures was reported in the Wenchuan earthquake for those bridges with bearing sliding. In this paper, an experimental program was carried out to investigate the sliding behavior of laminated rubber bearings with typical configurations in China. The bearing was placed directly on a steel plate representing the embedded steel plate at the bottom of bridge girders, to create an elastomer-steel sliding surface. Experiment results showed that the behavior of bearings before obvious sliding could be approximated as a linear elastic response, with an effective shear modulus in the range of 610–1100 kPa. The sliding coefficients of friction were observed to be inversely related to the normal force, and positively related to the sliding velocity. An analytical model considering the sliding response of laminated-rubber bearings on steel plates was developed and calibrated. Numerical simulations were also conducted to compare the proposed model to the model with typical Coulomb's friction. Results from the numerical simulations indicated that the vertical earthquake caused differences of bearing displacement response between these two models. And this difference would be more significant as the intensity of vertical earthquake increased.

1. Introduction

Economical laminated rubber bearings, which usually have not been designed for seismic demand, are widely used in small to medium-span highway bridges of China, especially those simply supported girder bridges. The bearings mainly allow for thermal movement of the bridge superstructure at service-level conditions through shear deformation of rubber. As common practice, the bearings are placed directly between the superstructure and the substructure, with no restraints among them other than friction (Fig. 1) [1,2]. The past 2008 Wenchuan earthquake occurred in western regions of China caused severe damage to highway bridges, especially those small to medium-span girder bridges. Damage investigation [3,4] revealed that the typical damage of these bridges included: sliding between the laminated rubber bearing and the girder (Fig. 2), shear keys failure, destruction of expansion joints and abutment, and even span collapse. On the other hand, no visible damages or only minor cracks were observed in piers for those bridges with bearing sliding. Such phenomena were also reported in the 1999 Chi-Chi earthquake [5–7].

The seismic fusing is an innovative and effective design strategy, which has been implemented in new and existing structures, including buildings and bridges [8–10]. In fact, owing to the installation practice, the laminated rubber bearings are prone to slide along the steel plates embedded in the upper girders during a large earthquake and potentially provide an isolated response for the system. The bearing sliding can act as structural fuses, to cause a period elongation and reduce the force demands on the substructure. The concept is just in accordance to the *fusing strategy* specified in AASHTO [11], which allows for a seismic fusing mechanism designed between elastic superstructure and substructure. Connecting components, such as bearings, isolation devices and energy dissipation devices can be introduced as the fusing mechanism to limit energy build-up of the bridge system. The Illinois Department of Transportation (IDOT) of the USA has investigated a quasi-isolation design and construction method for typical highway bridges in Illinois [12–15]. The key points of the proposed

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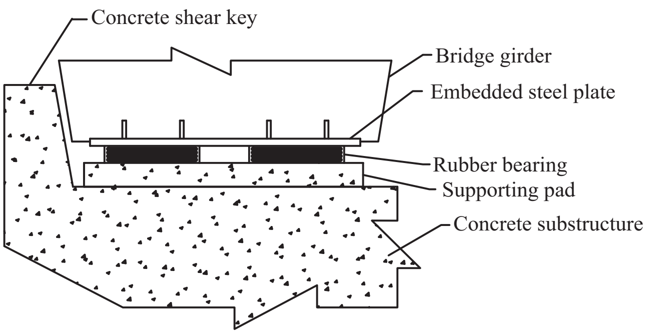

Fig. 1. Typical layout of laminated-rubber bearings.

Fig. 2. Sliding of laminated-rubber bearings.

quasi-isolation rely on some sequential fusing (i.e., sliding, yielding, or rupture) of specific components (i.e., laminated elastomeric bearings, side retainers, or steel fixed bearings) to limit forces that can be transferred down through the bridge system.

The seismic behavior of laminated rubber bearings with large shear strains has been studied extensively. Konstantinidis et al. [16] have conducted experiments on the shear response of laminated rubber bearings, which are not bonded to top or bottom steel plates, and concluded that the bearings can withstand up to 225% shear strains, limited by the roll-off response of the bearing. Further horizontal displacement beyond the roll-off state will cause the bearing sliding along steel plate. Steelman et al. [17] have investigated the shear and sliding response of laminated rubber bearings on concrete surfaces subjected to seismic demands, and found that the bearing exhibited an approximately linear elastic response with the maximum shear strain of 125–250% before sliding. When the bearings began to sliding on the concrete substructure with an initial friction coefficient of 0.25–0.5, the force-displacement hysteretic hoops of bearings became wide, displaying stable and powerful energy dissipation capacity. However, the previous studies mainly focused on how a laminated rubber bearing behaved during an earthquake. No practical analytical models have been proposed to describe the seismic behavior of laminated rubber bearings, especially when the bearing sliding is considered.

The sliding behaviors of laminated-rubber bearings may be quite sensitive to the variation of axial load. The variation of axial load is mainly induced by the vertical seismic excitation during the earthquake. Besides, horizontal seismic excitation may cause the significant variation of axial load on bearings in some bridge configurations. For example, for multi-span simply supported girder bridges in which the bearings are usually placed eccentrically with respect to the vertical axis of the piers in longitudinal direction, the longitudinal seismic excitation can cause the variation of axial forces in the bearings due to the vertical motions of the deck and the rotations of the pier caps [18].

This paper describes a laboratory testing program of typical laminated rubber bearings in China. The object of the testing is to investigate the seismic performance of laminated rubber bearings as fuses, including the shear and sliding response. An analytical model is developed based on the experimental results, to accurately describe the fusing characteristics of laminated rubber bearings.

2. Testing background

2.1. Bearing specimens and test setup

The testing consists of two types of laminated rubber bearing specimens listed in Table 1. GYZ 400 × 84 specimens are those full-scale bearings commonly used at a 25 m span T-girder simply-supported highway bridge. GJZ 200 × 21 specimens are representative of those appropriate for use at the quarter-scale shake-table model of a 25 m span T-girder bridge. All specimens are designed and manufactured according to the Chinese bearing guidelines (CBG JT/T-4) [18]. Fig. 3 shows the configuration details of these two types of specimens. The bearing dimensions, elastomer layer thickness and steel shim thickness all satisfy the tolerance requirements specified in the GBG JT/T-4. Normally a bearing specimen is composed of cover elastomer layers, internal elastomer layers and steel shims, and the thickness t and the quantity n of these components are listed in Table 1. The cover elastomer layers are placed at the top and the bottom of specimens. The internal elastomer layers in the specimens are of uniform thickness, and so are the steel shims. The elastomer used for the elastomer layers is composed of neoprene with a required hardness of 60 ± 5. The tensile strength of elastomer is 17 MPa, and the ultimate elongation is 400%. The steel used for the steel shims is carbon structural steel with a yield strength of 235 MPa and a ultimate strength of 370 MPa. The ultimate elongation of the steel is 26%, and the impact absorbing energy is 27 joule. As for the fabrication of bearing specimens, the steel shims are firstly prepared for vulcanization by using abrasive blasting to provide an initial roughened surface, and then treating the surface with a proprietary chemical bonding agent. The elastomer layers are finally connected to the steel shims through the process of vulcanization. The quality control requirements for the bearing specimens are well satisfied, and there is no initial delamination occurring for all the test specimens.

The tests were carried out in the State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University using the experimental apparatus shown in Fig. 4. Vertical loading was imposed on the bearing specimens through a 3000kN capacity hydraulic servo actuator. The hydraulic servo actuator can automatically adjust itself to make the vertical load maintained at a specified target value regardless the horizontal deformation of the bearing. The horizontal actuator can provide a maximum loading of 500 kN with the maintained vertical loading. Rollers which were placed under the horizontal loading arms made it sure that the vertical and horizontal actuators worked simultaneously to approximately simulate the loads condition during an earthquake, where the bearings were subjected to horizontal inertial forces at the same time sustaining gravity load. The frictional forces occurred at the surface of rollers were minor and could be neglected.