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SHAKE-TABLE TESTS OF A BRIDGE MODEL WITH DIFFERENT TRANSVERSE UNSEATING-PREVENTION DEVICES

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Abstract

Damage investigation of highway bridges after the 2008 Wenchuan earthquake showed that typical types of damage included: sliding between the laminated-rubber bearing and the bridge girder, shear keys failure, excessive girder displacements and even span collapse. As part of a major research on the seismic response of highway bridges with economical laminated-rubber bearings in China, a quarter-scale, two-span bridge model was tested on shake tables at Tongji University. The model was subjected to a series of ground motions with different characteristics. The seismic behaviors of different unseating-prevention devices (concrete shear keys and X-steel damper) were investigated and compared in the test. The construction and testing of the bridge model, and the selected experimental results were discussed in the paper. Conclusions drawn from the test are as follows: (1) the sliding of laminated-rubber bearing can perform as a structural fuse that protect piers from severe damage; (2) the properly designed concrete shear keys can effectively restrain the bearing displacements, but will result in relatively large seismic demand of piers; (3) due to the powerful energy dissipation, X-steel dampers perform well in controlling the bearing displacements, and at the same time, mitigating the seismic demand of piers. It is suggested that the X-steel damper can be used along with the laminated-rubber bearings, to improve the seismic performance of highway bridges.

Keywords: Wenchuan earthquake; bridge model; laminated-rubber bearing; unseating-prevention devices; shake table tests

1. Introduction

Small to medium-span highway bridges, including simply-supported and continuous ones, are widely used in China. These bridges are characterized by the installation of economical laminated-rubber bearings that allow for thermal movement of the superstructure, and concrete shear keys that prevent excessive transverse movement from service-level to small earthquake loadings. Common practice [1] is that the bearings are placed directly between the bridge girder and the concrete superstructure, with on horizontal restraint other than friction (Fig. 1). The top surface of the bearing is in direct contact with the steel plate embedded in the bridge girder. Surveys conducted after the 2008 Wenchuan earthquake [2, 3] revealed that sliding between the laminated-rubber bearing and the girder (Fig. 2) was a common phenomenon for small to medium-span highway bridges. Due to the bearing sliding, excessive girder displacement occurred and finally led to damage of concrete shear keys (Fig. 3), expansion joints and abutments. On the other hand, for bridges suffering from the bearing sliding, damage to piers and foundations was minor. This is obvious that the bearing sliding can actually perform as structural fuses, providing some protection for the substructure.

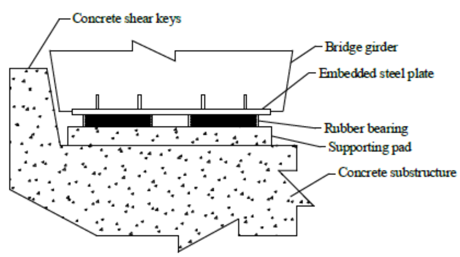


Fig. 1 – Bearing arrangement

Fig. 2 – Bearing sliding

Fig. 3 – Concrete shear keys failure

Concrete shear keys are usually installed along with laminated rubber bearings to provide transverse support for the bridge girder. However, during the Wenchuan earthquake, concrete shear keys did not perform well as expected. Severe shear keys damages, such as diagonal cracking, flexural failure or even totally shearing off were observed during the earthquake. Regarding the drawbacks of concrete shear keys, X-steel dampers [4] are proposed and applied as transverse unseating-prevention devices for bridges. X-steel damper is an added damping and stiffness (ADAS) device which has been widely used in building frames [5, 6]. The damper can dissipate substantial energy during an earthquake through the yielding of steel plates.

To investigate the seismic response of bridges with economical laminated-rubber bearings in China, an experimental program was conducted at Tongji University. The main objectives of this research program were: (1) to validate the fusing effect of laminated-rubber bearing sliding, (2) to investigate and evaluate the seismic behaviors of different unseating prevention devices, including concrete shear keys and X-steel dampers.

2. Bridge prototype

A nonskewed simply-supported highway bridge with RC box girders is selected as the prototype in the study (Fig. 4). The bridge girder has a span length of 30m and is supported on three, two-column bents through laminated-rubber bearings. The bents were of the same height and column diameter, making the bridge regular and symmetric. The laminated-rubber bearing installed in the prototype bridge is circular, with a dimension of 600-130mm (diameter-height).

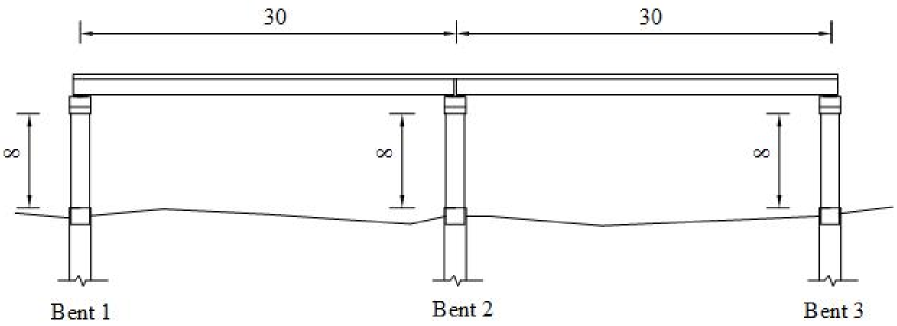


Fig. 4 – Elevation of the bridge prototype [unit: mm]

3. Bridge model

The test bridge was a quarter-scale geometric model of the prototype highway bridge (Fig. 5). As it was not feasible to construct the complex box girders for quarter-scale dimension, steel plates were designed to approximately model the bridge superstructure. The dimensions of the steel plates were designed so that the bending moments of inertia about the strong and weak axes matched the inertias of the prototype quarter-scale equivalent. Furthermore, steel blocks were placed on the steel plates to provide added masses for the model.

Bent columns of the model have a diameter of 0.4m, and a height of 2.0m. There are 16 longitudinal steels with a diameter of 12 mm arranged in the columns corresponding to a steel ratio of 1.4%. The transverse reinforcement in the column was a circular hoop with a volumetric reinforcement ratio of 0.9% and satisfied the provisions of the Chinese code [7]. Steel with the specified yield strength of 335Mpa was used, and the specified concrete compressive strength was 40Mpa. The actual average measured yield stress for steel reinforcement was 331Mpa, and the compressive strength at the time of testing was 41Mpa.

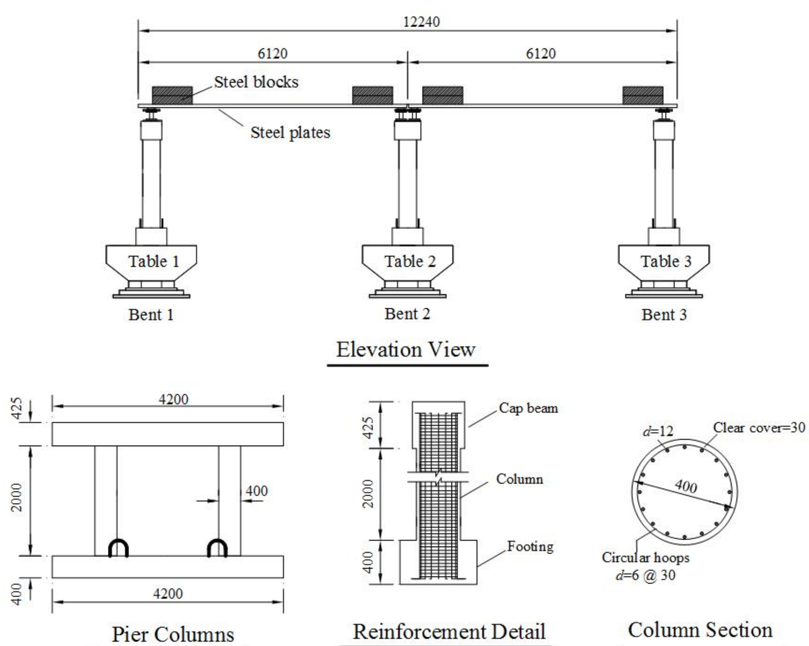
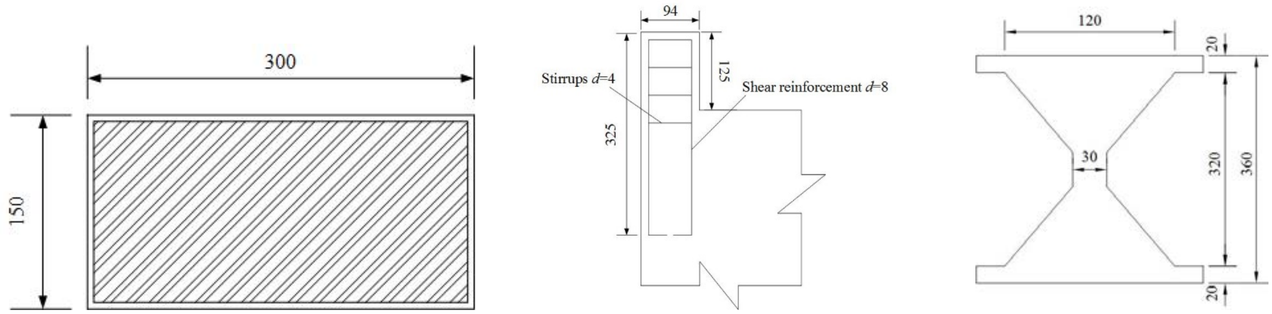


Fig. 5 – Details of the bridge model [unit: mm]

Fig. 6 shows the details of laminated-rubber bearing, concrete shear keys and X-steel damper. Laminated-rubber bearings of the model were designed so that the plan area and shear stiffness matched those of the prototype bearings scale equivalent. Two scaled bearings were placed on each bent to provide support for the superstructure. Strength of concrete shear keys in the model was designed as 30% of the dead load vertical reaction at middle bent, which satisfied the seismic design criteria for shear keys in CALTRANS [8]. X-steel dampers in the model have a yield strength of 21 kN, accounting for 7.5% of the dead load vertical reaction at middle bent.



(a) Laminated-rubber bearings (b) Concrete shear keys (c) X-steel dampers

Fig. 6 – Details of laminated-rubber bearings, concrete shear keys and X-steel dampers [unit: mm]

4. Construction and test setup

The bridge model consisted of three two-column bents and two steel plates with some additional steel blocks. The bents were constructed individually and were fixed on the three shake tables. Steel plates, simulated as superstructures, were placed directly on the laminated-rubber bearings whose bottom surface was attached to the cap beams. Steel blocks were anchored on top of the steel plates to provide necessary masses for dynamic simulation. Concrete shear keys were casted on both sides of the cap beam in transverse direction. Steel cantilever arms were installed to transmit the seismic force of the superstructure to concrete shear keys (Fig. 7a). X-steel dampers were anchored between superstructure and cap beam to provide transverse restraint for the superstructure (Fig. 7b). Fig. 7c shows the completed bridge model in the laboratory.

(a) Installation of concrete shear keys (b) Installation of X-steel dampers (c) Completed bridge model

Fig. 7 – Test setup of the bridge model in the laboratory

5. Instrumentation

The response of the bridge model was measured using 184 sensors consisting of strain gauges, accelerometers, displacement transducers, and load cells (Table 1). Displacement transducers were used to measure the displacements of superstructures, bearings, concrete shear keys, X-steel damper, and pier columns. The acceleration responses of superstructures, pier columns and shake tables were measured using 28 accelerometers. In addition, load cells were installed in the model to measure bearing force, shear keys force and steel damper force.

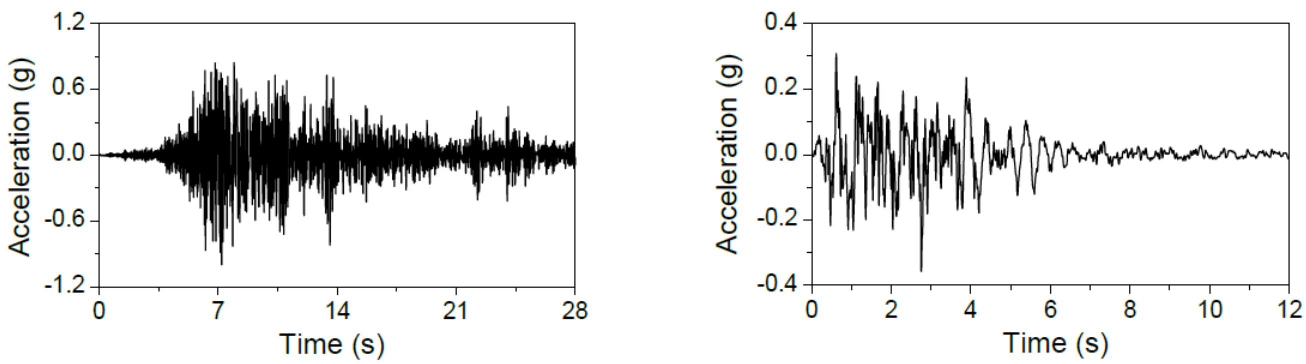
Table 1 – Instrumentation summary for the bridge model

Instruments	Measured responses	Number
Strain gauge	Column longitudinal reinforcement strain	72
	Column transverse reinforcement strain	36
Accelerometers	Superstructure acceleration	10
	Pier acceleration	15
	Shake table acceleration	3
Displacement transducers	Superstructure displacement	4
	Bearing displacement	8
	Pier displacement	18
	Steel damper displacement	6
	Concrete shear keys displacement	6
Load cells	Bearing forces	6
	Steel damper forces	6
	Concrete shear keys	6
Total		196

6. Testing protocol

The bridge model was subjected to two ground motions in transverse direction. One is based on East-West Shifang-Bajiao record from the 2008 Wenchuan earthquake. The second one is an artificial ground motion which is synthetized to match the design spectrum of the prototype bridge. Fig. 8 shows the input ground motions with a compressed time axis and unscaled amplitude. The selected motions were applied only in the transverse direction.

For the bridge model, three cases were tested: (1) without devices (only laminated-rubber bearings provide transverse support for the superstructure), (2) with X-steel dampers, and (3) with concrete shear keys. For the case without devices, both the two ground motions were applied in sequential runs of increasing earthquake intensity. The Wenchuan ground motion was applied to the bridge model with concrete shear keys, and the artificial ground motion was applied in the case with X-steel dampers.



(a) Wenchuan (b) artificial

Fig. 8 – Input motions with compressed time axis and unmodified amplitude

7. Test results

7.1 Observed performance

In the case without devices, the laminated-rubber bearings exhibited small shear deformation when the input earthquake intensity was small. With increase of earthquake PGAs, the bearing shear deformation increased gradually until sliding between the bearings and the superstructures was initiated. After the bearing sliding occurred, the sliding displacements of the bearings increased with increase of earthquake intensity. Besides, significant bearing residual displacements were observed after the excitation.

In the case with X-steel dampers, the bearings and the steel dampers deformed back and forth with small deformations at a low-amplitude excitation. When the earthquake PGAs increased, the deformations of bearings and steel dampers increased. After the earthquake excitation, steel dampers exhibited small permanent plastic deformations.

Fig. 9 shows the damage progression of concrete shear keys in the case with concrete shear keys. The bearings deformed little due to the restraints of concrete shear keys at low-amplitude excitation. With the increase of input earthquake PGAs, damage was firstly observed at concrete shear keys with slight concrete cracking and spalling occurring. Then, severe concrete spalling and diagonal cracks appeared and gradually extended down to the cap beam zones. After the last run of excitation, the concrete shear keys were nearly sheared off and there is gap occurring between the superstructure and the shear keys.

(a) cracking initiation (b) cracking progression (c) severe cracking and spalling (d) shear keys failure

Fig. 9 – Damage progression of concrete shear keys during the tests (Wenchuan record)

7.2 Acceleration response

Fig. 10–11 show the peak acceleration amplification factors along the model height. The results of the cases with X-steel dampers and with concrete shear keys are compared with those of the case without devices, respectively. When the bridge model is installed with X-steel damper or concrete shear keys, the acceleration amplification factors along the substructure height are smaller, in comparison with the case without devices. However, for the superstructure acceleration response, the amplification factors are relatively larger than those in the case without devices. And with the increase of earthquake PGAs, the differences of acceleration amplification factors will become more significant.

7.3 Bearing displacement response

Fig. 12–13 show how the peak bearing displacements and residual displacements vary with the earthquake PGAs, respectively. For the case without devices, the bearings exhibit large displacement response at high PGAs due to the bearing sliding effect, which greatly increases the risk of span collapse. The bearing sliding also leads to considerable bearing residual displacements after excitation. Both X-steel dampers and concrete shear keys can effectively reduce the bearing displacements. The bearing residual displacements can also be decreased by the unseating-prevention devices. As an example, for the artificial record at PGA=0.6g, the peak bearing displacement in the case without devices is 56 mm and the corresponding residual displacement is 13.3 mm, while the values are 29.3 mm and 0.4 mm in the case with X-steel damper. For the Wenchuan record at PGA=1.0g, the bearing peak and residual displacements in the case without devices are 35.5 mm and 8.5 mm, in comparison with the values of 22.3 mm and 1.4 mm in the case with concrete shear keys.

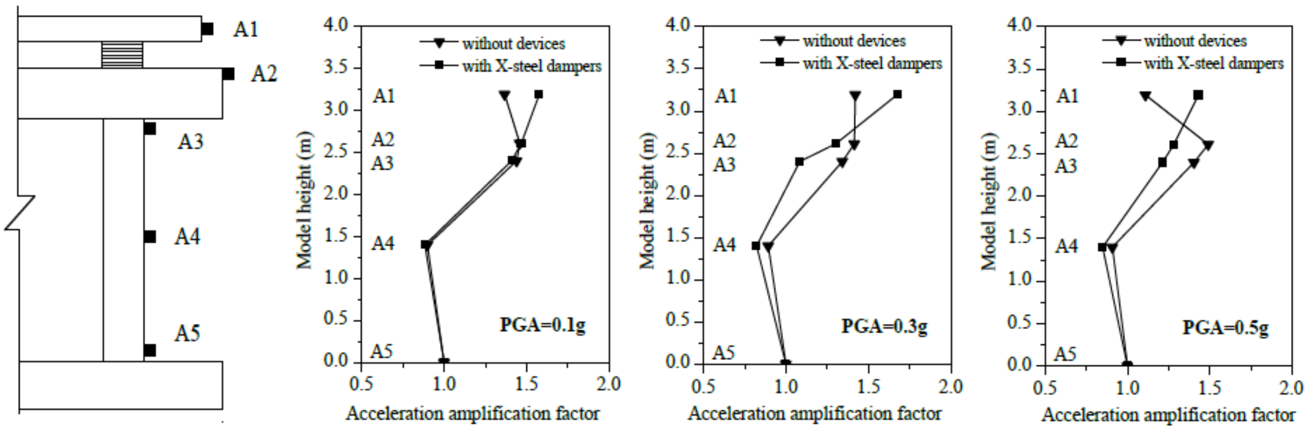


Fig. 10 –Variation of peak acceleration amplification factors along the model height (artificial record)

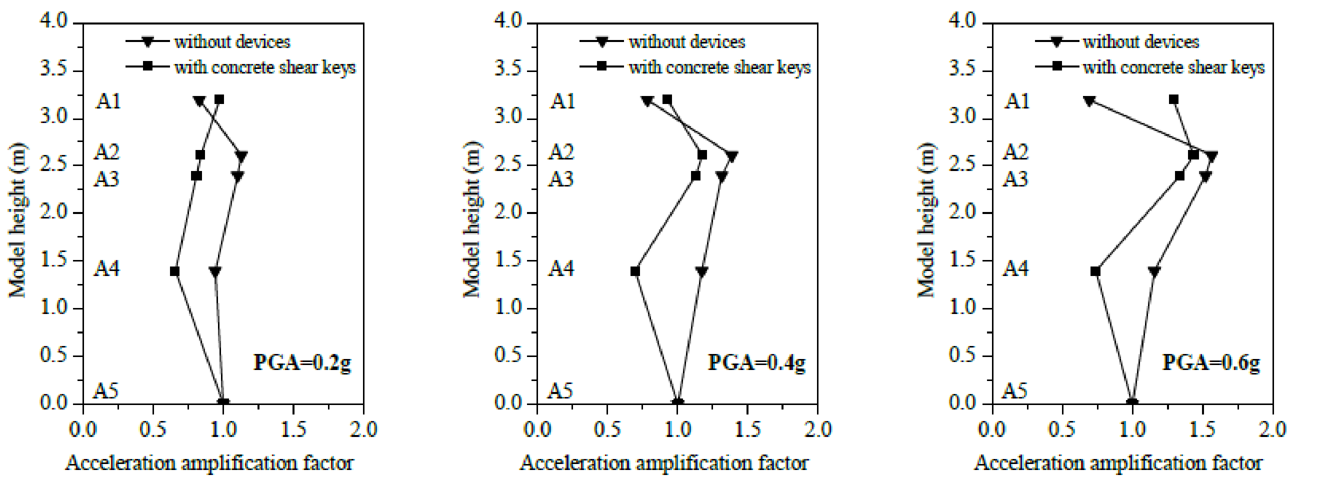


Fig. 11 –Variation of peak acceleration amplification factors along the model height (Wenchuan record)

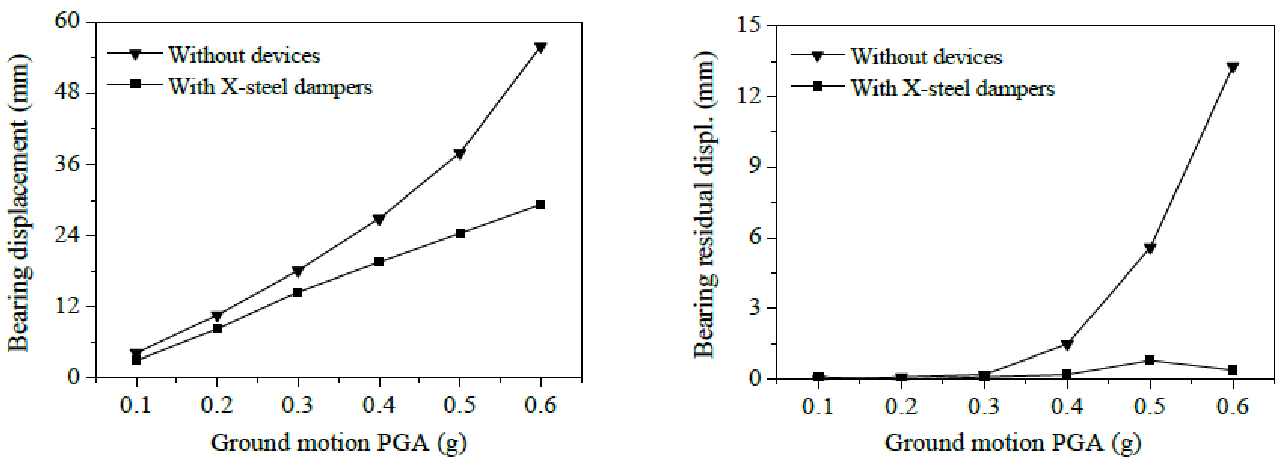


Fig. 12 –Bearing peak and residual displacements versus the earthquake PGAs (artificial record)

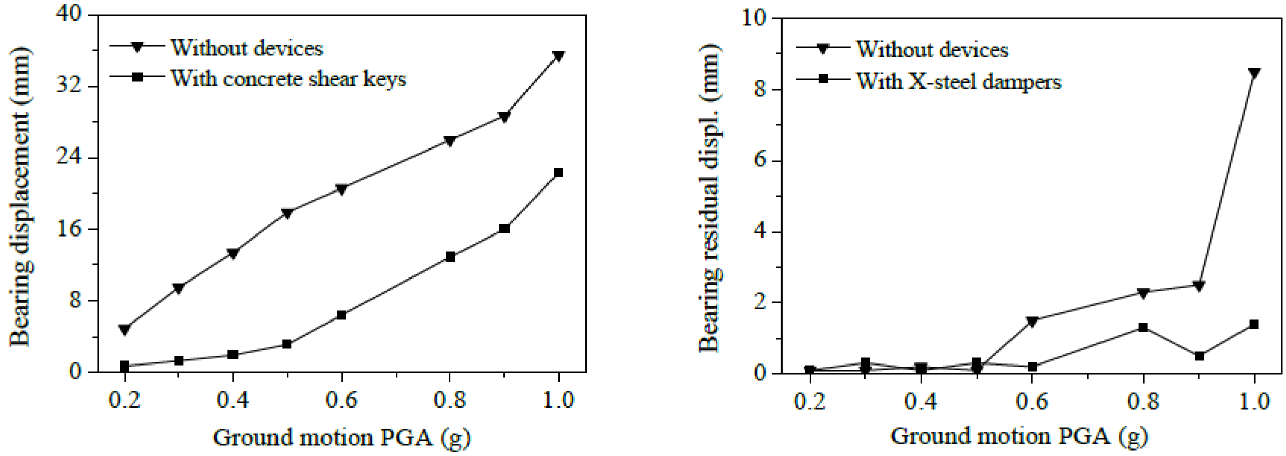
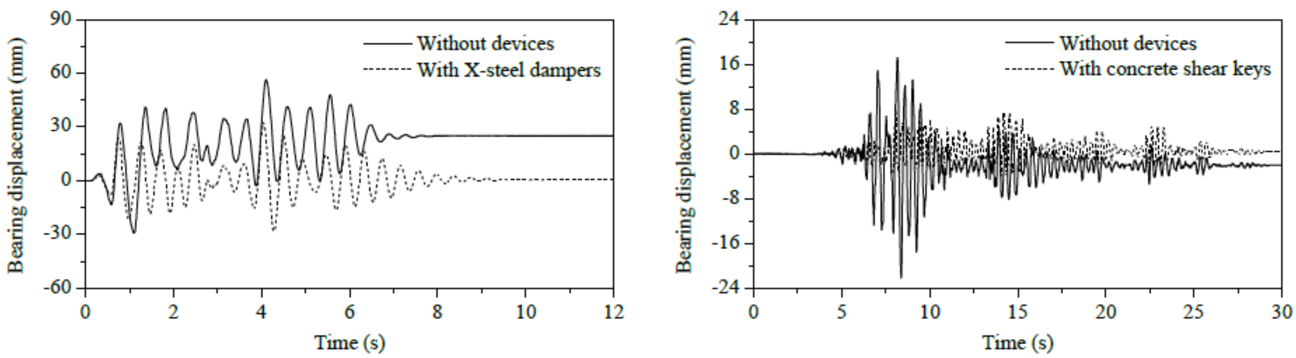


Fig. 13 –Bearing peak and residual displacements versus the earthquake PGAs (Wenchuan record)

Fig. 14 shows bearing displacement histories for the artificial and the Wenchuan earthquake at PGA=0.6g. The time histories curves schematically present how the X-steel dampers and concrete shear keys restrict the bearing displacements. As seen from Fig. 14, with the earthquake excitation, the bearings gradually deviate from their initial positions and produce large residual displacements in the case without devices, especially when the artificial record is applied in the bridge model. In the cases with unseating prevention devices, the bearing peak displacements and residual displacements can be controlled to a large extent.

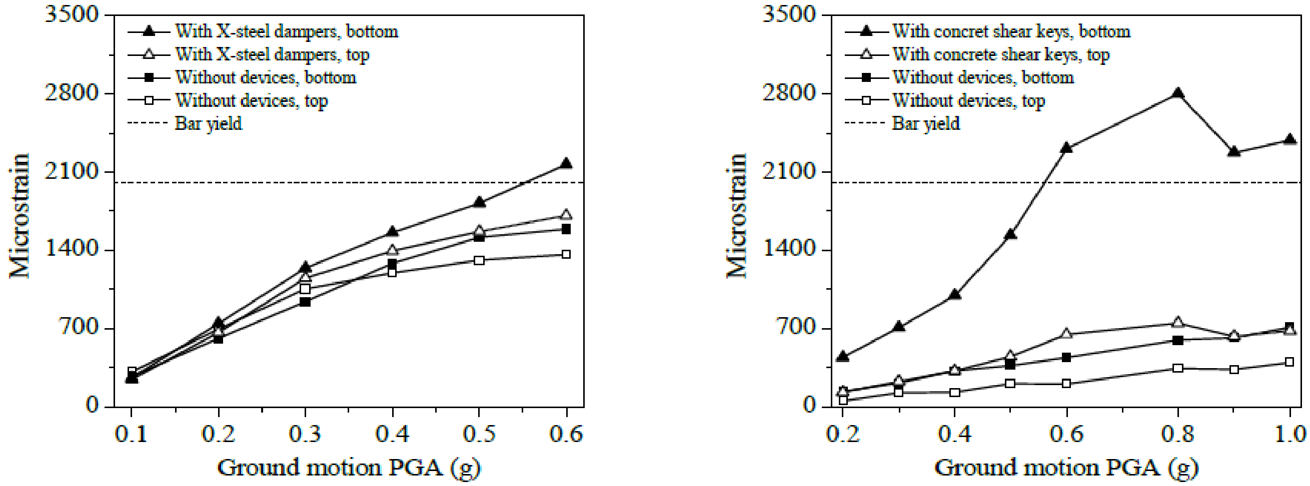


(a) artificial record (b) Wenchuan record

Fig. 14 – Bearing displacement histories at PGA=0.6g

7.4 Strains in longitudinal column bars

The peak measured tensile strains in longitudinal bars for the artificial record and the Wenchuan record are shown in Fig. 15a–b, respectively. For a two-column bent pier subjected to transverse earthquake excitation, both the bottom and top of the column will be the critical zones. Generally, the peak strain in bars increase with the increase of earthquake PGAs. In the case without devices, the longitudinal bars do not yield for either artificial record or Wenchuan record. This indicates that the bearing sliding can effectively isolate the inertial forces of the superstructure, and thus protect the piers from severe damage. In the cases with unseating prevention devices, the peak strains in longitudinal bars are larger, in comparison with the case without devices. The maximum ratio of peak strain to yield strain for bars is 1.08 for artificial record (occurred at PGA=0.6g), and 1.40 for Wenchuan record (occurred at PGA=0.8g). Besides, Fig. 15a–b also indicate that the top of the column is less vulnerable to the transverse earthquake excitation than the bottom zone, as the peak strains in the top zones are generally smaller than the bottom zone strains.

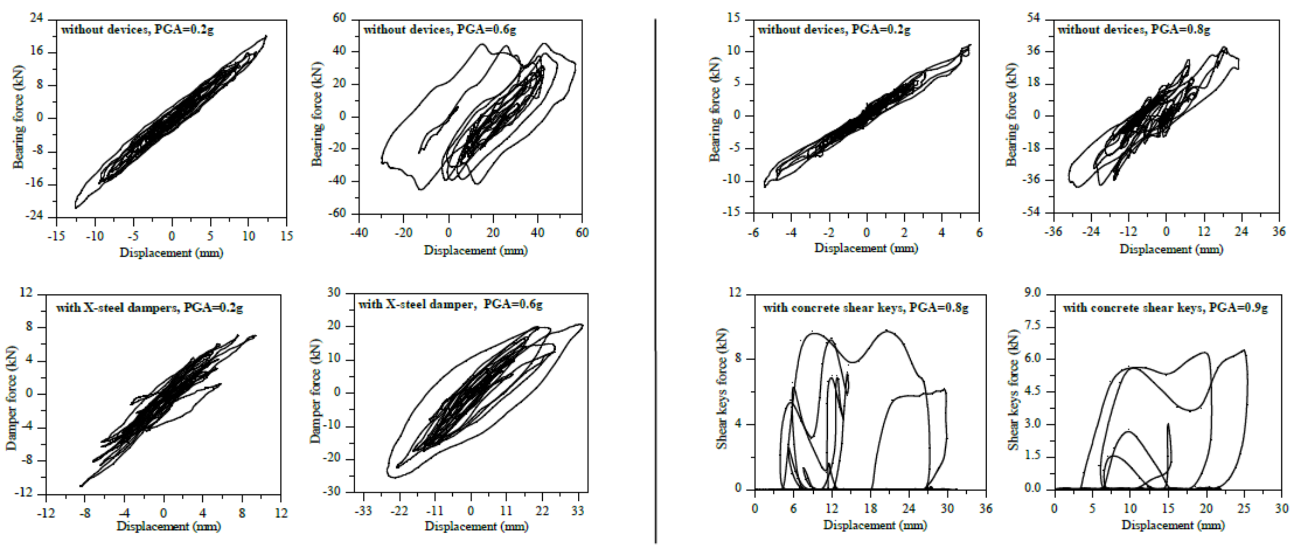


(a) artificial record (b) Wenchuan record

Fig. 15 – Peak measured strains in longitudinal column bars

7.5 Force-displacement relationships response

Fig. 16 shows the measured force-displacement curves of bearings, X-steel dampers and concrete shear keys. The bearing exhibits an approximately linear elastic response at low-amplitude excitation. With the increase of earthquake PGAs, the bearing begins to slide and the force-displacement curves become flat and wide. In the case with X-steel dampers, the steel dampers yield and undergo plastic deformations with the increase of earthquake PGAs. The force-displacement curves of steel dampers at high-amplitude excitation are relatively wide, indicating good energy dissipation in dampers. The force-displacement hysteretic curves of concrete shear keys at PGA=0.8g and PGA=0.9g are plotted in Fig. 16b. As concrete shear keys are compression-only devices, the compressive force-displacement curves are shown in the figures. Gaps between the superstructure and shear keys are noted in the hysteretic curves due to the minor damage of shear keys during the previous excitations. The shear keys force reached its peak at PGA=0.8g with a value of 98 kN. With the increase of PGAs, the shear keys suffer severe damage with lateral resistance decreased. At PGA=0.9g, the peak shear keys force is only 63 kN. The hysteretic curves also reveal that X-steel dampers have more powerful and stable energy dissipation capacity than concrete shear keys.



(a) artificial record (b) Wenchuan record

Fig. 16 –Cumulative measured force-displacement curves of bearings, X-steel dampers and concrete shear keys

8. Conclusion

This paper presented the design, construction and testing of a two-span, RC bridge model with laminated rubber bearings and different unseating prevention devices on the shake tables at Tongji University. The following conclusions are the main findings of the experimental results:

(1) Shake table tests revealed that the sliding between laminated-rubber bearings and superstructure is prone to occur during large earthquakes. The bearing sliding can effectively isolate the seismic forces of the superstructure, and thus protect the substructure from severe damage.
(2) Although the properly designed concrete shear keys can restrain the bearing displacements, they will result in large seismic demands of substructures. The longitudinal steels in pier columns will yield at high-amplitude excitation due to the inclusion of concrete shear keys.
(3) X-steel dampers were proved to dissipate substantial energy during an earthquake through yielding of steel plates. As transverse unseating prevention devices, X-steel dampers perform well in controlling the bearing displacements, and simultaneously, mitigating the seismic demands of substructure. It is suggested that X-steel dampers be used along with laminated-rubber bearings, to improve the transverse seismic performance of highway bridges.

9. Acknowledgments

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