EXPERIMENTAL STUDY OF HIGHWAY BRIDGES WITH POUNDING EFFECTS SUBJECT BI-DIRECTIONAL EARTHQUAKE EXCITATIONS

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ABSTRACT :

This paper presents an experimental study to investigate the pounding effects of highway bridges under bi-directional earthquake excitations. A 1:20 scaled elevated bridge model with two segments is designed and manufactured. The superstructures of the bridge model are supported by using linear rubber bearings, and the gap size between the neighbouring segments is set to be 3.5mm according to the geometric scaling. The pounding effects of the highway bridges under bi-directional ground motions are investigated by shake table tests. A series of tests are carried out for the bridge model with large gap size under two bi-directional ground motions, including Taft and Kobe earthquake records. Then, the similar tests of the bridge model with small gap size are also conducted to investigate the pounding effects between the adjacent superstructures. The experimental results show that the bi-directional pounding between the adjacent segments of the highway bridges will significantly increase the acceleration responses of the structures. The highway bridges in earthquake area should be properly designed to lighten the pounding damage of the structures.

KEYWORDS:

Pounding, highway bridge, shaking table test, bi-directional earthquake, seismic response

1. INTRODUCTION

Most long, multi-span bridges have expansion joints to lighten the influence of the shrinkage, creep and the thermal effect of the concrete. During the severe earthquakes in the past several decades, pounding damage of the highway bridges was widely observed at the expansion joints with insufficient separation distance due to the difference in dynamic characteristics of the adjacent structures and the spatial variation of the earthquake ground motions. The velocity exchange between the adjacent superstructures during pounding will abruptly increase the accelerations of the superstructures, and the collision between the adjacent girders or the slabs will also generate huge additional impact forces to the structural members, resulting in the spalling of the concrete and the damage of the piers and abutments, even the unseating of the bridge girders.

Pounding damage of the highway bridges has been widely observed in the severe earthquakes during the past several decades. In the Loma Prieta earthquake of 1989, the difference in the natural frequencies between the adjacent frames of the lower roadway and piers supporting an upper-level deck of the southern viaduct section at the China Basin in California resulted in severe impacts and substantial damage (Priestley 1996). During the 1994 Northridge earthquake, significant pounding damage was also observed at the expansion joints at the Interstate 5 and State Road 14 interchange located approximately 12 km from the epicenter (Pantelides 1998). Survey after the 1995 Kobe earthquake also revealed that the expressway deck had considerable longitudinal movement, thus resulting in significant pounding damage at the intermediate hinges and the concrete piers (Vomartiin et al. 1995).

Due to the complexities involved in the process of structural pounding, a rigorous analysis of highway bridges with pounding effects is difficult. Recently, two kinds of modeling techniques, named as the stereomechanical approach and contact element approach, are mainly used to analyze the contact phenomena of the bridges and buildings under earthquake excitations. The stereomechanical approach is a macroscopic attempt to model impact. It is assumed that the impact is instantaneous, and the momentum conservation principle is used along with the coefficient of restitution to model the impact (Goldsmith, 2001). Alternatively, the contact element approach uses the spring element, damping element or their combination in conjunction with a gap element to represent the impact force during pounding. Several linear and nonlinear impact models for simulating the 1D point-to-point impact, including the linear spring model (Muthukumar and DesRoches, 2006), linear viscoelastic model (Jankowski *et al.*, 1998), nonlinear elastic model (Chau *et al.*, 2003) and nonlinear viscoelastic model [Jankowski, 2005], have been developed for investigating the dynamic impact of the structures. Muthukumar and DesRoches (2006) comprehensively investigated the cogency of the above impact models in capturing the seismic pounding response of adjacent structures. Furthermore, Zhu *et al.* (2002) developed a 3D contact-friction model to precisely simulate the arbitrary contacts of the bridge structures during pounding. Experiments have also been conducted to verify the proposed pounding model.

This paper presents an experimental study to investigate the pounding effects of highway bridges under bi-directional earthquake excitations. A two-segment bridge model with geometric scaling of 1:20 with is designed and manufactured. The superstructures of the bridge model are supported by using linear rubber bearings, and the gap size between the neighbouring segments is set to be 3.5mm according to the geometric scaling. The pounding effects of the highway bridges under bi-directional ground motions are investigated by shake table tests. For comparison, a series of tests are carried out firstly for the bridge model with large gap size under three bi-directional ground motions, of Taft and Kobe earthquake records. Then, the pounding experiments of the bridge model with small gap size are also conducted to investigate the pounding effects between the adjacent superstructures. The experimental results show that the bi-directional pounding between the adjacent segments of the highway bridges will significantly increase the acceleration responses of the structures. The highway bridges in earthquake area should be properly designed to lighten the pounding damage of the structures.

2. EXPERIMENTAL SET-UP

2.1 1:20 scaled bridge model

The experiments are performed on a tri-axial shaking table of size 5m×5m at the Institute of Engineering Mechanics of China Earthquake Administration in Harbin. The payload of the shaking table is 350kN, and the working frequency ranges from 0.5Hz to 40Hz. The shaking table is capable of providing the maximum accelerations of ±1.0g in the two horizontal directions and ±0.7g in the vertical direction, respectively. The maximum displacements and velocities in the horizontal and vertical directions are up to 8cm, 5cm and 50cm/s, 40cm/s, respectively.

A two-span isolated bridge model is designed based on the Standard Drawings of Highway Bridge of China. The span length and the deck width of the prototype structure are 36m and 24m, respectively. The decks are supported on the piers with the height of 16m through isolators. The mass of each superstructure is 628 ton. The gap size of the expansion joint of the prototype structure is 7cm. In consideration of the structural properties of the prototype structure and the feasibility of the experiment on the shaking table, the geometric scaling of the two-span bridge model is selected at 1/20. To include the pounding effects in the experiments, the natural periods of the left and right segments of the bridge model is designed to be 0.47s and 0.40s, respectively, with the corresponding natural periods of the prototype structure of 2.10s and 1.80s. Based on the artificial mass simulation, the other model scales are calculated and listed in Table 1.

According to the model scales, an experimental model of the prototype highway bridge is designed and manufactured, as shown in Figure 1. The bridge model has two spans with the same clear span of 1.8m, width of 1.2m and height of 1.53m. The deck of each segment consists of a steel plate of 1.8m×1.2m×0.02m and an additional mass made of reinforce concrete, which is welded tightly on the steel plate through the embedded steel plate in the concrete, to form the deck with the mass of 2.5 ton. The substructure of the bridge model is composed of three piles made of the H-beam, and eight rubber bearings are installed to decouple the piles and the decks

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Table 1. Scaling factors of the bridge model

Parameter	Scaling factor	1:20 model	Parameter	Scaling factor	1:20 model
Length	l_r	1/20	Velocity	$l_r^{0.5}$	$1/\sqrt{20}$
Time	$l_r^{0.5}$	$1/\sqrt{20}$	Acceleration	1	1
Frequency	$l_r^{-0.5}$	$\sqrt{20}/1$	Force	l_r^2	1/400
Displacement	l_r	1/20			

Figure 1. Photographs of the bridge model

The gap size of the expansion joint of the bridge model is set as 3.5mm according to the geometric scaling. However, the dynamics of the bridge model without including the pounding effects will also be experimentally investigated in this study for comparison. To meet the requirement of the experiments without the pounding effects, part of the steel plates of the decks is cut to enlarge the expansion joint of 100mm, as shown in Figure 3(b). During the tests of structural model with pounding effects, a contact plate is installed in the left segment to comply with the original expansion joint of 3.5mm.

2.2 Rubber bearing

The height and diameter of the rubber bearings used in the experiments are 97.5mm and 100mm, respectively. The bearing consists of two steel endplates and 22 thin steel shims, among which 23 rubber shims with thickness of 1.5mm are vulcanized and bonded to the steel shims. To meet the designed natural periods of the bridge model, two kinds of rubber materials with shear modulus of 0.39MPa and 0.55 MPa are used to fabricate the rubber bearings for the left and right segments, respectively.

2.3 Instrumentation and measurement

To measure the bi-directional earthquake inputs of the shaking table, two accelerometers are installed on the shaking table platform. Eight accelerometers are also put on the two decks in two directions to measure the absolute accelerations of the superstructures. The relative displacement responses between the adjacent superstructures are obtained by using a LVDT sensor installed over the expansion joint. The bridge model is also instrumented with two LVDT sensors between the decks and piles to measure the deformations of the bearings.

A NI USB-6221 instrument, which has 16 A/D channels and 2 D/A channels, in conjunction with the Matlab/simulink package, is used to perform the data acquisition. The measured displacement and acceleration signals are sent to the A/D channels of the data acquisition instrument after conditioning. During the tests, the structural responses are measured with a sampling frequency of 5000Hz to capture the instantaneous impact of the bridge model.

3. EXPERIMENTAL RESULTS

In order to evaluate the pounding effects, the dynamic responses of the bridge model in two different structural cases are experimentally studied:

(1). Structure without pounding effects. In this case, the contact plate is removed, and the gap size of the expansion joint is set as 100mm. The adjacent decks of this bridge model do not contact with such large separation spacing under the earthquake excitations.

(2). Structure with pounding effects. The contact plate is installed to form the expansion joint with the gap size of 3.5mm. The adjacent decks collide with the small gap size of the expansion joint during earthquakes.

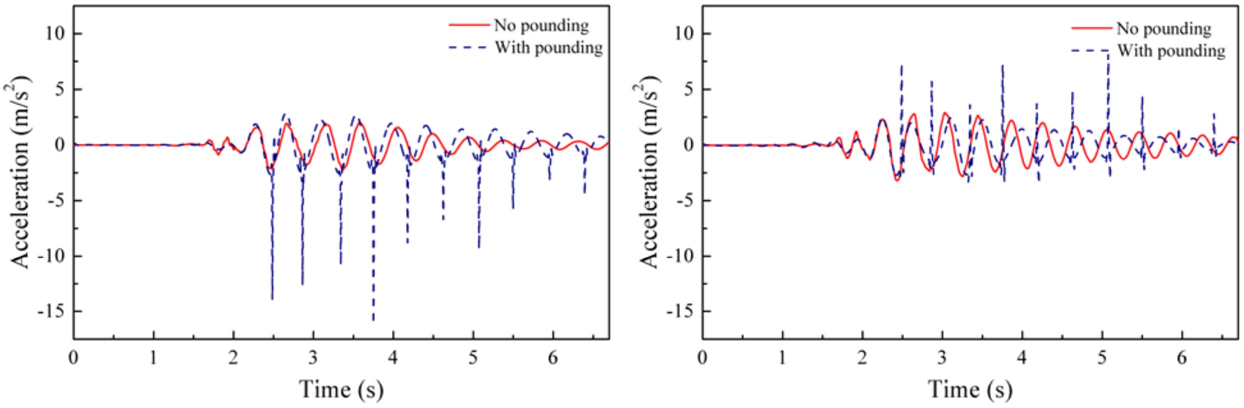
Two earthquake records are chosen as the ground motion inputs of the shake table:

(1). Kobe (JMA Station FN Component), 1995 Kobe earthquake with PGA equal to 825.0 cm/s^2 and 308.6 cm/s^2 in the X and Y directions.

(2). Taft (Taf111 component), 1952 Kern Country earthquake with PGA equal to 177.8 cm/s^2 and 258.5 cm/s^2;

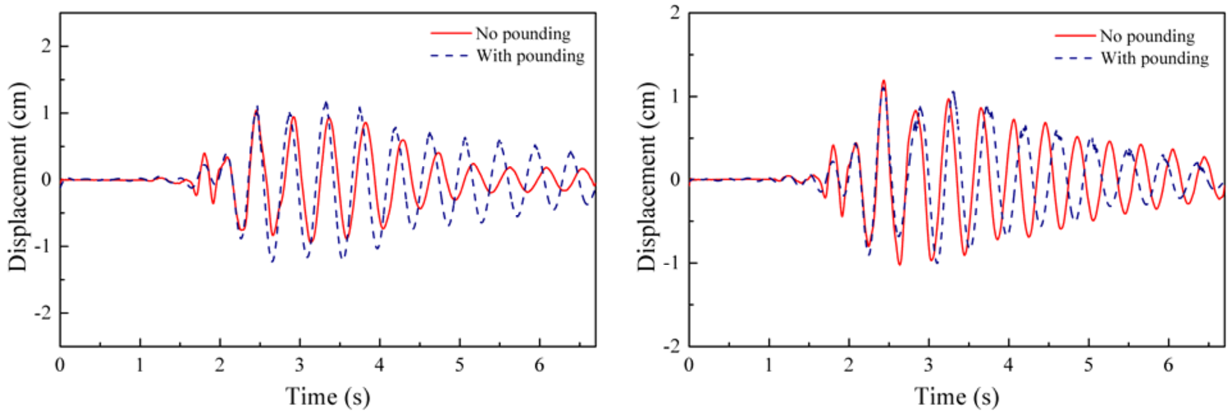
Time increment of the original ground motion records is compressed with the time-scale factor. The X-directional PGA of the earthquake records are scaled to 600.0 cm/s^2, respectively, to excite large enough deformation and prevent the damage of the rubber bearings. The Y-directional PGA of the earthquake records are also scaled with the same scaling.

The base-isolated bridge model without including the pounding effects is firstly conducted to evaluate the responses of the uncontrolled model under Kobe earthquake excitations. The time histories of the X-directional absolute acceleration responses of the bridge model under the Kobe earthquake are shown in Figure 2. It is observed that, in the case of the Kobe earthquake, the absolute accelerations in the X direction of the left and right decks are measured to be 2.24m/s^2 and 3.20m/s^2, respectively. The corresponding displacements of the bearings are 1.04cm and 1.19cm, as shown in Figure 3. The test results indicate that the pounding may occur if the gap size of the expansion joint is set as 3.5mm.



(a) Left segment (b) Right segment

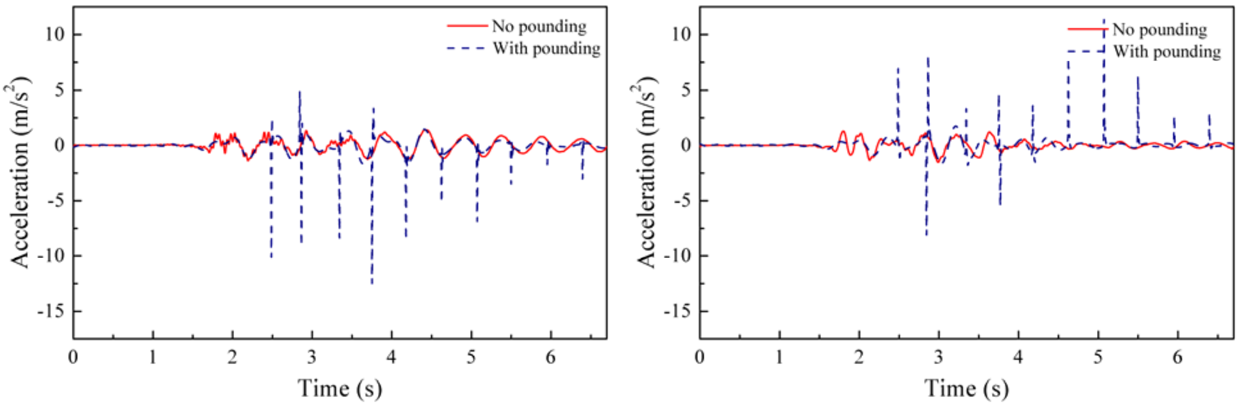
Figure 2. The X-directional absolute acceleration of the bridge decks under the Kobe earthquake



(c) (d)

(a) Left segment (b) Right segment

Figure 3. The X-directional displacement of the bridge decks under the Kobe earthquake



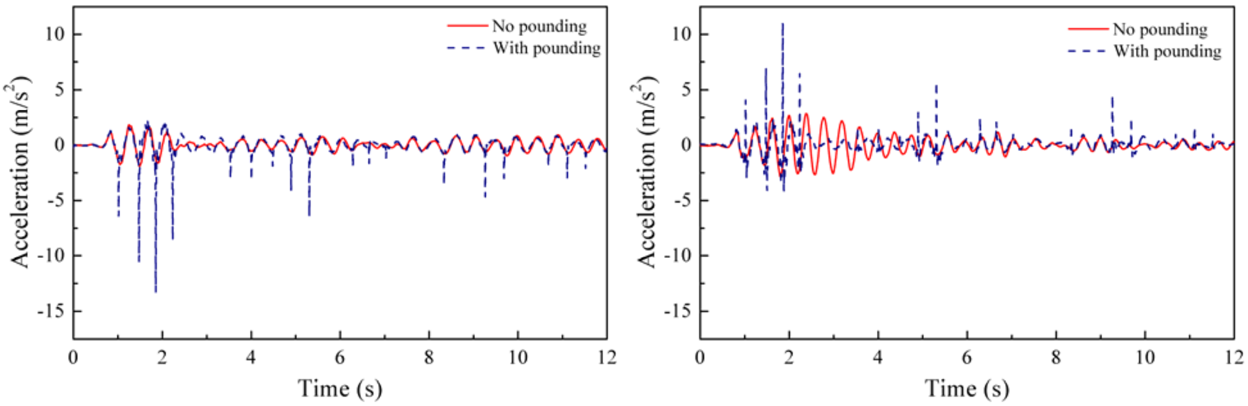
(a) Left segment (b) Right segment

Figure 4. The Y-directional absolute acceleration of the bridge decks under the Kobe earthquake

The structural responses of the bridge model including the pounding effects by installing the contact point under the El Centro earthquake are also presented in Figure 2. As observed in the figure, several sharp peaks appear in the time histories of the absolute acceleration responses due to the pounding with the installation of the contact point. The adjacent decks collide 10 times during earthquake. As an example, the peak absolute accelerations of the left and right decks increase to 16.16 m/s^2 and 8.12m/s^2, respectively. The displacement of the left-segment bearings increases from 1.04cm to 1.23cm. The displacement of the right-segment bearings reduces to 1.11cm.

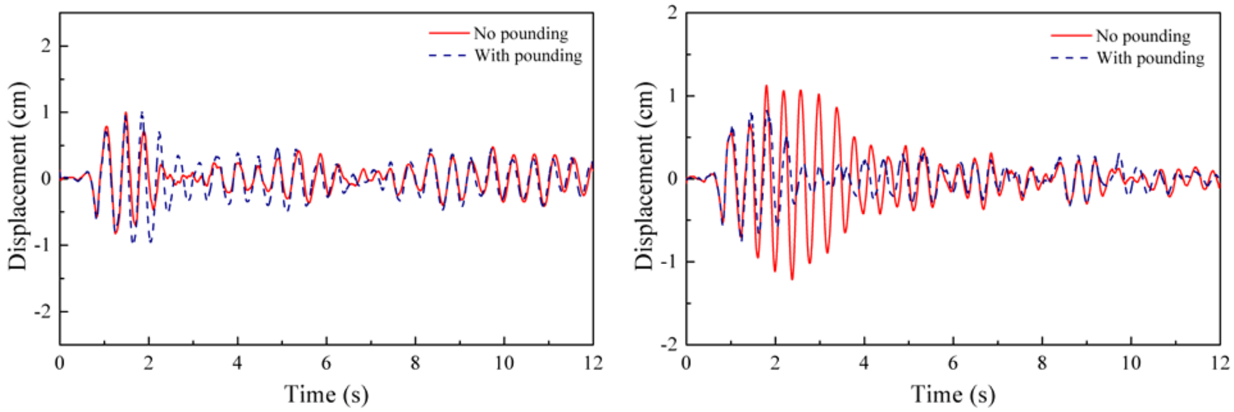
The absolute accelerations of the bridge decks in the Y direction are also shown in Figure 4. As evidence from the figure, the absolute accelerations in the Y direction of the bridge decks also significantly increase due to the pounding between the adjacent superstructures. The peak absolute accelerations of the left and right decks without including the pounding are found to be 1.42m/s^2 and 1.52 m/s^2. However, the absolute accelerations increase to 12.49 m/s^2 and 11.36 m/s^2.

The absolute accelerations of the bridge decks under Taft earthquake in the X and Y directions are also shown in Figure 5 and Figure 7. The displacement of the rubber bearings also shows in Figure 6. It can be seen from those figures that the same phenomena can also be found for the bridge decks under the Taft earthquake.



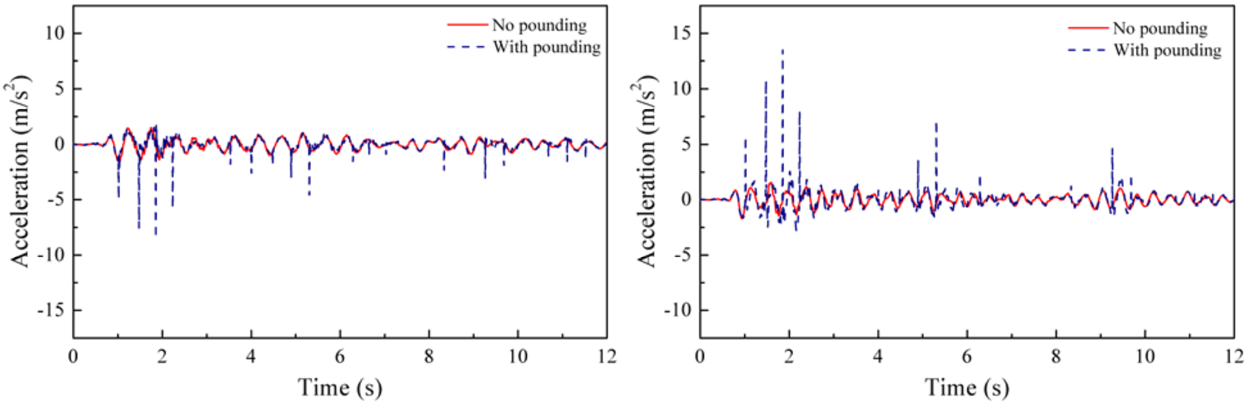
(a) Left segment (b) Right segment

Figure 5. The X-directional absolute acceleration of the bridge decks under the Taft earthquake



(a) Left segment (b) Right segment

Figure 6. The X-directional displacement of the bridge decks under the Taft earthquake



(a) Left segment (b) Right segment

Figure 7. The Y-directional absolute acceleration of the bridge decks under the Taft earthquake

4. Colusions

This paper experimentally investigates the pounding effect of a base-isolated highway bridge under bi-directional earthquake excitations. A variety of shaking table tests for structure without pounding and with pounding are conducted. From the shaking table tests, it is found that the bi-directional pounding between the adjacent segments of the highway bridges will significantly increase the acceleration responses of the structures. The highway bridges in earthquake area should be properly designed to lighten the pounding damage of the structures.

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