Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria

Experimental study of seismic pounding effects on bridge structures subjected to spatially varying ground motions

Bipin Shrestha[1], LiXiang He[2], Kaiming Bi[3], Hong Hao[4], Weixin Ren[5]

1. Corresponding Author. PhD Candidate, School of Civil and Mech. Engineering, Curtin University, WA 6102.
   Email: bipinsh01@gmail.com

2. PhD Candidate, Dept. of Civil Engineering, Central South University, Hunan, China.

3. Lecturer, School of Civil and Mech. Engineering, Curtin University, WA 6102.

4. Professor, School of Civil and Mech. Engineering, Curtin University, WA 6102.

5. Professor, Dept. of Civil Engineering, Hefei University of Technology, Hefei, China.

Abstract

Pounding and unseating damages to bridge decks have been commonly observed in all major earthquakes. Since pounding always causes certain level of damages to structures and there is no reliable and efficient design method to mitigate pounding damage yet, in recent years, structural pounding have received a significant research attentions. However, most of the studies are confined to numerical simulation. Experimental studies are very scarce. Moreover, only a few studies on the pounding response of adjacent bridge structures have considered spatially varying ground motion although it is acknowledged that earthquake ground motion spatial variation is inevitable and it results in out-of-phase vibrations that may lead to pounding. This paper presents experimental study conducted with two sets of large scale bridge models (1:6) to identify the influences of spatially varying motion on the pounding response of adjacent bridge frames and the effectiveness of pounding mitigation devices. Spatially varying ground motions are applied to bridge models using newly installed two independent shake tables at national laboratory of high speed railway construction, Central South University, China. This paper presents the experimental investigation particularly focusing upon the test model design, sensor installation, test methodology and brief overview of damages observed.

Keywords: Shake table testing, pounding, spatially varying ground motions, mitigation devices

1. INTRODUCTION

Post seismic surveys of damages after major earthquakes have revealed many bridges suffered substantial damages due to seismic-induced structural pounding. For example, in 1994 Northridge earthquake, 1995 Hyogo-Ken Nanbu earthquake, 1999 Chi-Chi earthquake, and 2008 Wenchuan earthquake, intensive pounding and unseating damages to bridge structures due to out-of-phase vibrations between adjacent spans were observed. In more recent earthquake events, pounding damages to building and bridges were also observed during Chilean earthquake (Kawashima et al., 2011) and the 2011 Christchurch earthquake (Chouw and Hao, 2012). Pounding of the adjacent structures, in general, resulted in minor to moderate damages on the bridge structures, often resulting in partial or complete closure of the bridge immediately after an earthquake event. However, in a few cases pounding of the adjacent bridge elements resulted in collapse of the bridge spans due to unseating.

Pounding and unseating are caused owing to relative displacement between adjacent bridge structures. When the relative closing displacement is larger than the gap width at an expansion joint, pounding occurs. On the other hand, when the relative opening displacement is larger than the seat length, unseating of bridge span occurs. One of the significant factors that induce relative displacements of extended structures such as bridges is spatial variation of seismic ground motions. Although spatial variation of ground motions is inevitable due to seismic wave propagation and different local soil condition along the length of bridge, owing to the difficulty in modeling, only a few researches in the past have considered this phenomenon in analyzing the relative displacement responses (i.e. pounding and unseating damages) of the adjacent bridge components.

Pounding is a complex phenomenon involving damage due to plastic deformation, local cracking and crushing due to impact and friction when adjacent components are in contact with each other. For better performance of bridge structure, pounding phenomenon needs to be well understood and incorporated in the design of the bridge structures. Previous studies and field investigation have clearly revealed that pounding of adjacent bridge structures results in large impact forces, acceleration pulses and transfer of force between the adjacent structures that could amplify the opening relative displacement between the adjacent structures. However, there is no consensus on the effects of pounding on the response of the bridge piers. Some studies (Ruagrassamee and Kawashima 2001) suggested pounding to be detrimental, while others (Kim and Shinozuka 2003; Malhotra 1998) concluded pounding to have less severe effect on the response. These contradicting observations indicate the need for further study including the large scale experiments to identify the effects of pounding on bridge structural responses.

Though there had been significant number of researches on pounding response between adjacent structures, most of the studies were conducted numerically. Experimental studies are rare. This is due to the complexity as well as the cost involved in conducting such experiments. Previous studies (Guo et. al. 2009; Weiser et al. 2012) performed the experimental investigation on the pounding response and damage mitigation in bridge structures. However, these studies considered only the uniform ground motions thus may not realistically present the pounding responses. Recently, Li et al. (2012) investigated the pounding response of the adjacent structures to spatially varying ground motion using three shake tables. Though, the spatially varying ground motion was considerd, the similitude law was not strictly enforced when constructing the models of a very small scale (1:125). Therefore, the testing result gave some indications of spatially varying ground motion's effects on bridge responses, but could not represent the damage associated with pounding of the adjacent bridge elements.

During an earthquake both pounding and unseating damages are possible because of the closing and opening relative displacement between adjacent bridge structures. To mitigate the possible pounding and unseating damages some codes, such as Japanese Highway Code (2004), suggest using restrainers and rubber bumper together. However, it fails to provide detail procedure on the design of such device as only limited research are conducted on its effectiveness. Previous investigation (Shrestha et al. 2014) found that combining rubber bumper with restrainers could be very effective on mitigating pounding and unseating damages in bridge structure. This experiment extends the previous numerical study by conducting the experimental investigation on effectiveness of using rubber bumpers with restrainers to mitigate relative displacement induced damages in bridge structures.

This paper presents details of the experimental study on two large scale bridge models conducted at Central South University. A series of tests on large scale bridge models was conducted using multiple shake table testing system. The purposes of these testing are listed below.
1) Analyzing the effect of spatially varying ground motion on the bridge response.
2) Evaluate effectiveness of using the rubber bumpers and restrainers to mitigate pounding damages.
3) Comparison of efficacy of various pounding mitigation devices.
4) Evaluate the effects of rocking foundation on the response of the adjacent bridge frames.

2. EXPERIMENTAL MODEL

The bridge models for the experiment were based on the prototype bridge consisting of two frames of length 50 m each. The test models, scaled to 1:6, was properly designed and constructed according to the scaling law as indicated in Table 1. In order to simulate inelastic deformation of the structure, reinforced concrete of the same grade as the prototype bridge was used for the model. Two bridge models, each consisted of two concrete bridge frames with post-tensioned girder (rigid T-shape girder) were prepared. The two model bridges were mainly tested for the two conditions, i.e. without any mitigation device and with pounding and unseating mitigation devices placed at the expansion joint of the bridge. The length of each experimental bridge frames was 8.33 m and the total length of the bridge model was 16.67 m. To simply the model abutments were not included in the bridge model. The test was conducted progressively by gradually increasing the ground motion intensity and spatial variation until safe operational capacity of the shake table was reached. The peak acceleration value that could be safely applied was about 1 g. Bridge response quantities such as relative displacement between bridge spans, forces, accelerations, and strains at the strategic locations were recorded. The Overall geometry of the prototype and the model is summarized in Table 2.

The bent of the bridge model frame consisted of two square piers. The size of the model pier was 0.25 m by 0.25 m with 1.23% longitudinal steel ratio. The specified concrete strength was 30 MPa and yield strength of the steel was 400 MPa. The superstructure concrete strength was 45

MPa. The model bridge decks were post-tensioned by 2-15 mm diameter tendons on each girder of the bridge. The Self weight of a bridge frame was 3.79 tonnes. The foundation weighted 1.95 tonnes. Weight of a bridge frame model including the foundation was therefore 5.74 tonnes. Additional weights of 15.6 tonnes were placed on each frame, thus the total weight of each frame was 21.34 tonnes. The total weight of the bridge model was 42.68 tonnes. Figure 1 presents the picture of the bridge model with additional mass placed over it.

Table 1. Scale ratios of the model structure

Physical quantity	Similitude	Scale factor(N)
Length, L	N_L	6
Acceleration, a	N_a	1
Stiffness, E	N_E	1
Mass, M	$N_{M=} N_E N_L^2 / N_a$	36
Time, t	$N_t = \sqrt{(} N_L / N_{a)}$	2.45
Force, F	$N_F = N_M N_a$	36

Table 2. Overall Geometry of the Prototype and Model Bridge

Bridge Dimension	Prototype	Model
Total length (m)	100	16.66
Frame length (m)	50-50	8.33-8.33
Total width (m)	9.00	1.5
Box girder width(m)	6.00	1.00
Column height (m)	6	1
Column size (m)	1.5x1.5	0.25x0.25
Girder depth, bent (m)	2.4	0.40
Girder depth, end (m)	1.2	0.20

3. SHAKE TABLE AND INSTRUMENTATIONS

Recently, national laboratory of high speed railway construction, Central South University, China have built a facility to house four 6 DOF shake tables. This experiment used two shake tables that had been installed in the facility. Both the shake tables have the payload capacity of 30 tonnes and size of 4 m by 4 m.

As the primary objective of the experiment was to investigate pounding damages of the bridge the expansion joint of the bridge was heavily instrumented. Figure 2 shows the instrumentation details of the bridge and expansion joint. 5 accelerometers were placed in the longitudinal direction to record acceleration pulses that could be caused by pounding impacts. Additionally, four accelerometers were placed in transverse directions. Two LVDTs were placed at the two corners, as shown in Figure 3 (a), of the deck to measure the relative displacement at the joint. A load cell with the capacity of 5 tonnes was placed at the joint, as shown in Figure 3 (b) to measure restrainers force. Strain gauges were attached to the reinforcements embedded at the corner of the bridge deck to measure strain during an impact of the adjacent frames. Curvatures gauges were placed on the piers of both the frames at top and bottom plastic hinge locations. Strain gauges were attached to longitudinal and transverse reinforcements of the piers. In total 80 channel data logger were used for sensor that include accelerometers, displacement transducers, load cell and strain gauges.

Figure 1.Photograph of the bridge model

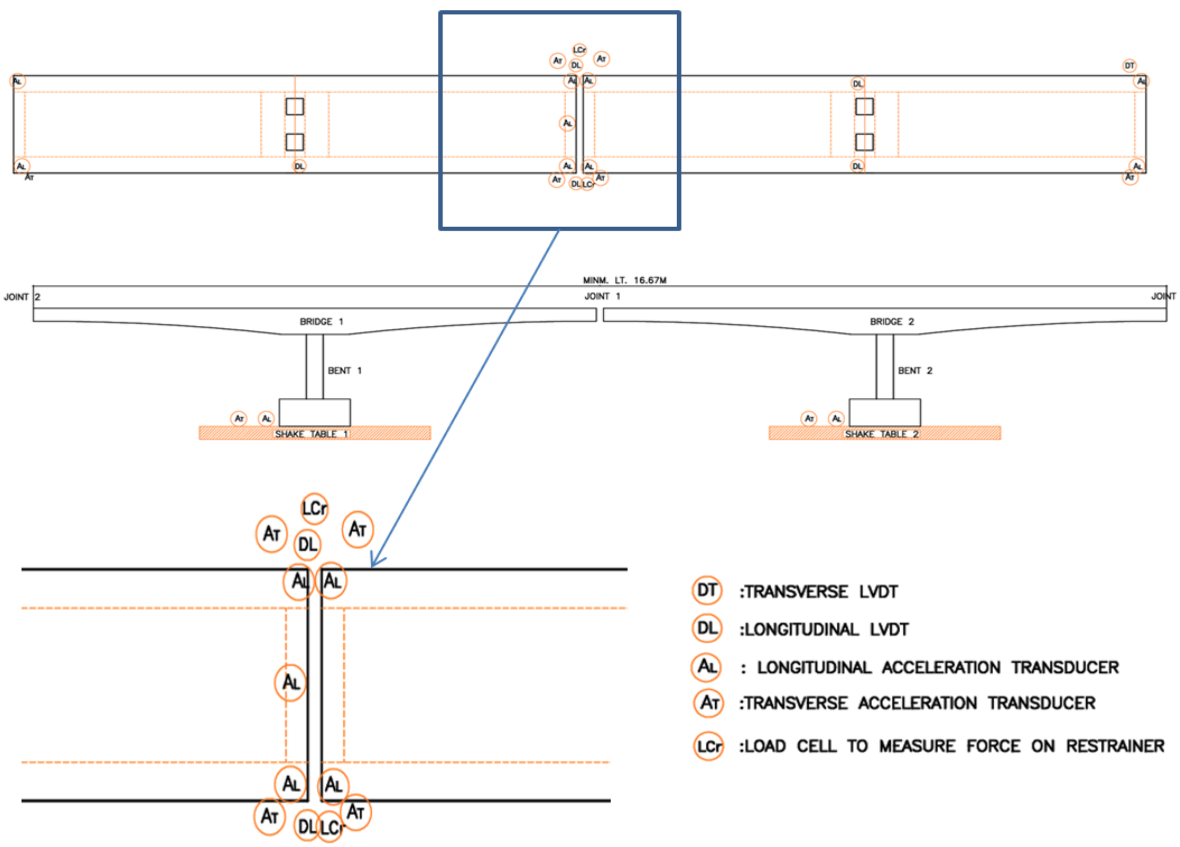
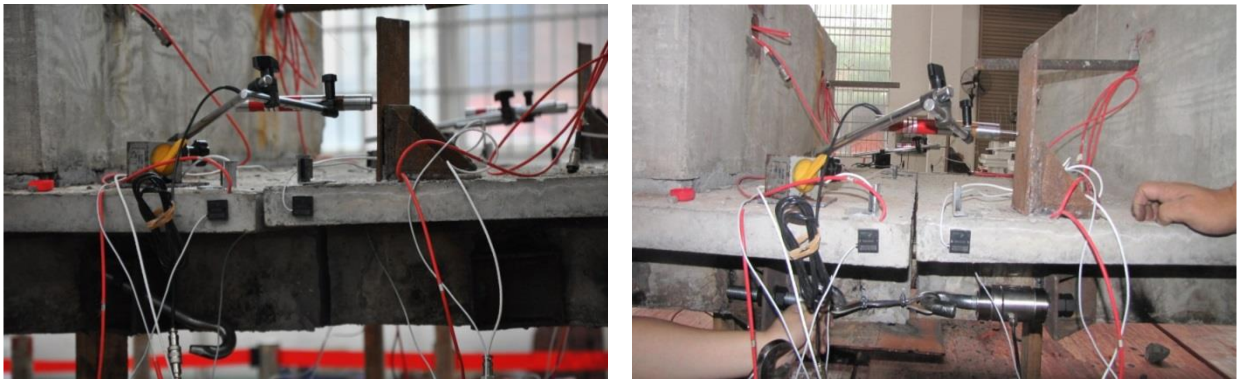


Figure 2. Instrumentation details of the bridges



(a) Bridge joint (North) (b) Bridge joint (South)

Figure 3. Photograph of measurement instruments at bridge joint

4. GROUND MOTIONS

For the experimental study ground motions for three soil classes based on Chinese Design Actions for Highway Bridges, as shown in Figure 4, were simulated. All of the spectrums as shown in the figure were normalized to 1g. In the experiment, the ground motion was increased incrementally in terms of spectrum based Peak ground Acceleration (PGA). The low intensity testing was conducted for PGA of 0.15 g and the final test was conducted for a PGA scaled to 0.9 g. To investigate the effects of coherency losses and soil site type on the response of the bridge frames 5 cases of ground motions as presented in Table 3 were considered. The apparent wave passage velocity and seismic wave incident angle were taken to be 500m/s and 60°, respectively. The simulated ground motions were compressed to account for scaling effects and target inertial mass. Moreover, to identify the effects of local site conditions on the spatially varying ground motions 6 more ground motion cases were simulated to represent different soil conditions and soil thickness at the supports of two frames.

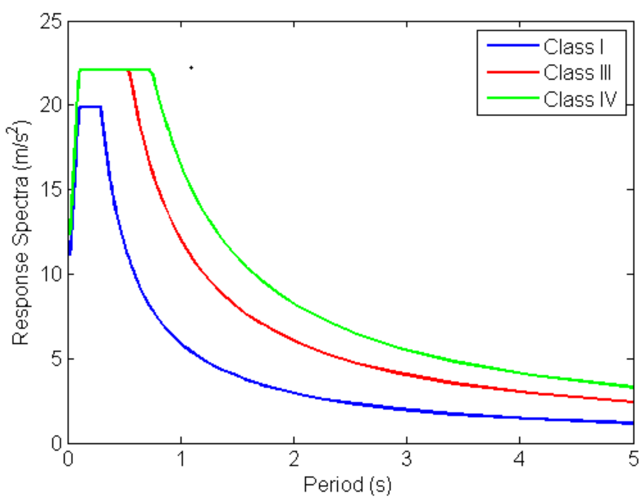


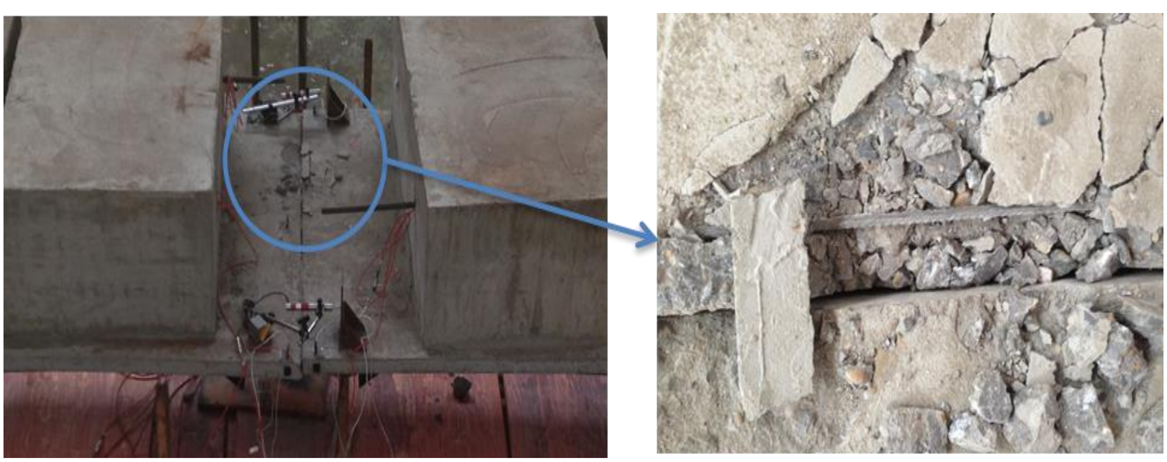
Figure 4. Normalized ground motion spectrum based on Chinese code.

Table 3. Cases of spatially varying ground motions

Cases	Site	Coherency
1	III(set2)	Highly (β=0.0004)
2	III (set2)	Intermediately (β=0.0008)
3	III (set2)	Weakly (β=0.0016)
4	I (set2)	Intermediately
5	IV (set2)	Intermediately

5. BRIDGE DAMAGES

Pounding between the adjacent frames was observed even at the low intensity motions of 0.15 g particularly for the spatially varying motion simulated for soil site class IV. As both the adjacent frames had similar natural frequency the observed pounding were directly attributable to spatially varying ground motions. Concrete spall damages were observed at the joint for spatially varying ground motions with PGA of 0.25 g. The damages observed at bridge joints are depicted in Figure 5. Figure 6 presents the acceleration recording at the joint of the bridge. Acceleration pulses indicating pounding of adjacent bridge decks are clearly visible in the figure. The presented result demonstrates that adjacent frames with identical natural frequency could pound against each other due to the out-of-phase motion caused by spatial variation of ground motions. These pounding forces could be large enough to cause localized damages at bridge joints even at low intensity ground motions. The damages observed at piers after the multiple runs of ground motions with PGA of 0.25g with fixed and rocking foundations are presented in Figure 6. As shown, the bridge piers with fixed foundation suffered significantly more cracks compared to the piers with rocking foundation. The observations from the experiment showed that rocking foundation could be an effective method to reduce the damages to the piers in the seismic events thought it may result in more frequent and severe pounding of adjacent frames.



(a) Damage at joint (b) Close up of damage

Figure 5. Picture of measurement instruments at bridge joint

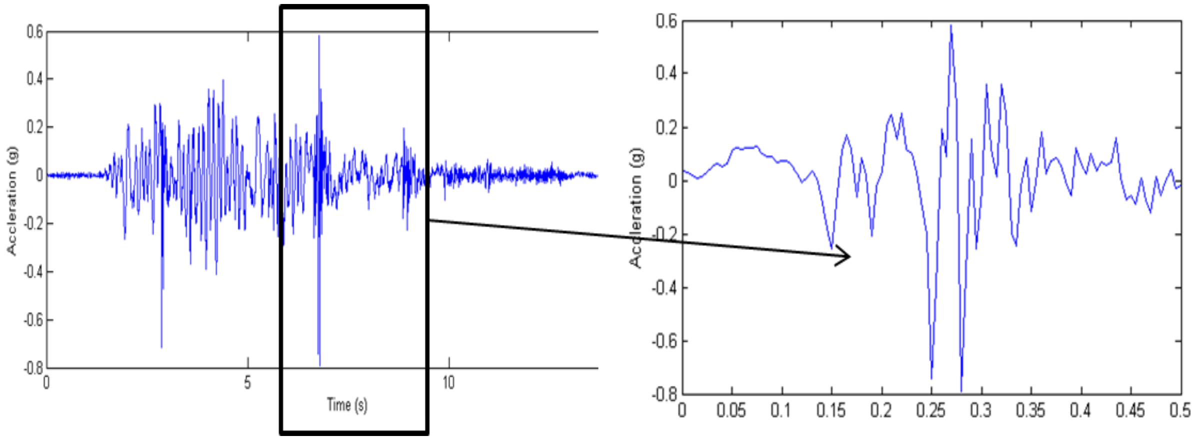


Figure 6. Acceleration pulses at joints due to pounding of adjacent decks

(a) Fixed foundation (b) Rocking foundation

Figure 6. Pier damage after multiple runs with PGA of 0.25 g

6. SUMMARY

This paper presents large scale experimental study conducted to identify the effects of spatially varying motions on bridge responses, particularly focusing upon the pounding damages. This paper focuses on the test model design, sensor installation and test methodology and brief reporting of observed damages from the test conducted recently at Central South University, China. Pounding of adjacent bridge structures was observed at the joint of the bridge frames having similar natural frequency even at low PGA of 0.15 g. Spall damages of concrete at joints was observed at PGA of 0.25 g. This demonstrates that adjusting the fundamental frequency of adjacent frames might not be sufficient to prevent pounding on bridges due to inevitable spatially variation of ground motions. The experiment provided some valuable results that are still being processed. These results of the experiment will be utilized to calibrate numerical models, which will be used for detail evaluation of bridge responses subjected to spatially varying ground motions.

ACKNOWLEDGEMENT

The authors acknowledge the partical funding provided by AustralianReseach Council (ARC) Linkage Project LP110200906 for carrying out this research.

REFERENCES

Japan Road Association (2004) Specification of highway bridges – Part V seismic design. 5th ed. (in Japanese).

Kawashima, K., Unjoh, S., Hoshikuma, J. I., & Kosa, K. (2011). Damage of bridges due to the 2010 Maule, Chile, earthquake. Journal of Earthquake Engineering, Vol 15, No 7, pp 1036-1068.

Chouw, N. and Hao, H. (2012) Pounding Damage to Buildings and Bridges in the 22 February 2011 Christchurch Earthquake. International Journal of Protective Structures, Vol 3, No 2, pp 123-140.

Ruangrassamee, A., & Kawashima, K. (2001). Relative displacement response spectra with pounding effect. Earthquake engineering & structural dynamics, Vol 30, No 10, pp 1511-1538.

Kim, S. H., & Shinozuka, M. (2003). Effects of seismically induced pounding at expansion joints of concrete bridges. Journal of engineering mechanics, Vol 129, No 11, pp 1225-1234.

Malhotra, P. K. (1998). Dynamics of seismic pounding at expansion joints of concrete bridges. Journal of Engineering Mechanics, Vol 124, No 7, pp 794-802.

Guo, A., Li, Z., Li, H., & Ou, J. (2009). Experimental and analytical study on pounding reduction of base-isolated highway bridges using MR dampers. Earthquake Engineering & Structural Dynamics, Vol 38, No 11, pp 1307-1333.

Wieser, J., Maragakis, E., Buckle, I., & Zaghi, A. E. (2012). Experimental Evaluation of Seismic Pounding at Seat-Type Abutments of Horizontally Curved Bridges. In 15th World Conference on Earthquake Engineering (15WCEE), Portugal.

Li, B., Bi, K., Chouw, N., Butterworth, J. W., & Hao, H. (2012). Experimental investigation of spatially varying effect of ground motions on bridge pounding. Earthquake Engineering & Structural Dynamics, Vol 41, No 14, pp 1959-1976.

Shrestha, B., Hao, H. & Bi, K. (2014) Effectiveness of using rubber bumpers and restrainers on mitigating pounding and unseating damage of bridge structures subjected to spatially varying ground motion, Engineering Structures , Vol. 79, pp 195-210.