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Pounding and Unseating Damage Mitigation on Bridge Structures subjected to Spatially Varying Ground Motions using Restrainers and Rubber Bumpers

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Abstract

Pounding and unseating damages to bridge decks have been observed in almost all previous major earthquakes. Pounding and unseating of adjacent bridge structures are attributed to relative displacement of adjacent structures caused by the out of phase vibration and/or the spatially varying ground motions. Most studies in the past had focused on the pounding and unseating of adjacent bridge structures caused by the out of phase vibration, resulting in the code specification of adjusting the fundamental periods of adjacent spans close to each other to mitigate the pounding effects. However, recent studies have highlighted that adjusting the fundamental periods of adjacent structures close to each other is not sufficient to prevent pounding and unseating damages owing to the relative displacement induced by spatially varying ground motions. This study investigates the effectiveness of using rubber bumpers as a shock absorbing device along with Shape Memory Alloy (SMA) restrainers or steel cable restrainers to mitigate pounding impacts and unseating damages on multi-span bridges subjected to spatially varying ground motions. The structural responses of bridges with and without mitigation devices are compared and discussed. The result indicates that the SMA restrainers combined with rubber bumpers could lead to superior performance.

Keywords: Structural pounding, shock absorbers, restrainers, shape memory alloy, spatially varying ground motions, multi-span bridge.

1. INTRODUCTION

Seismic pounding between girders and between girder and abutment in multi-span bridges has been commonly observed in almost all major earthquakes, for example, the 1989 Loma Prieta earthquake, 1994 Northridge earthquake, 1995 Hyogo-Ken Nanbu earthquake, 1999 Chi-Chi earthquake, and 2001 Bhuj earthquake. Pounding damage between adjacent bridge structures were also observed in the 2008 Wenchuan earthquake (Kawashima et al., 2009), 2010 Chile earthquake (Kawashima et al., 2011) and more recently the 2011 Christchurch earthquake (Chouw and Hao, 2012). Based on observations from past earthquakes, pounding can cause crushing and spalling of concrete at the impact locations, result in damage to column bents, abutments, shear keys, bearing pads and restrainers, and possibly contribute to the collapse of deck spans.

Restrainers have been in use since early 1970's as an effective device for preventing span collapse during an earthquake event. In subsequent earthquakes, their performances were well demonstrated. However, in large earthquakes such as the 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquake, a number of cases of inefficiency of steel restrainers were observed, with serious damage or even collapse of a number of bridges retrofitted with restrainers (Saiidi et al., 1993; Moehle 1995 ; Comartin et al., 1995). The inadequate performance of restrainers during large earthquakes is a result of the fact that the steel restrainers are designed to remain elastic; hence transfer large force to the bridge components (Selna et al., 1989). Additionally, when the ground shaking is strong enough to cause restrainer to yield, its effectiveness is greatly reduced for remainder of the ground motion due to the accumulation of plastic deformation. Recently to overcome the limitation of steel cables and bars, shape memory alloys (SMA) with super-elastic behaviour have been widely investigated. In these studies (DesRoches and Delemont, 2002; Andrawes and DesRoches, 2005; Padgett et al., 2010; Guo et al., 2012) SMA based restrainers have been proposed to avoid deck unseating, but the pounding impact mitigation between adjacent decks were not considered. It should be noted that the performance of restrainers depends on the relative displacement response of adjacent bridge structures. However, in most of the previous studies, uniform ground excitations along the bridge supports are assumed, which may not lead to accurate predictions of relative displacement between adjacent bridge structures and hence assessment of restrainers' performance under earthquake loading as ground motion spatial variation has been proven to significantly affect the relative responses between adjacent bridge structures (Chouw and Hao, 2008; Li et al., 2012).

Even though the destructive potential of structural pounding had been evident during almost all major earthquakes, there is still not sufficient guideline provided by the seismic design codes to prevent the harmful effects of pounding between adjacent bridge structures. Most of the bridge design codes suggest adjusting fundamental period of the adjacent structures close to each other as the only method to prevent pounding damage between adjacent structures. However, recent studies (Chouw and Hao, 2008; Chouw and Hao, 2009; Li et al., 2012; Chouw and Hao, 2005; Bi and Hao, 2013) demonstrate that only adjusting the fundamental period of the adjacent structures is not sufficient to avoid damaging pounding when bridge structure is subjected to spatially varying ground motions. A method of mitigating pounding damages could be the incorporation of layers of soft material, such as rubber on the expansion joints to act as shock absorber. Previous studies (Kawashima and Shoji, 2000; Abdel Raheem, 2009; Polycarpou and Komodromos, 2011) assessed the effectiveness of such an impact mitigation measure on the response of bridges and buildings. The incorporation of rubber shock absorbers on the expansion joints was found to be effective to mitigate large pounding forces and acceleration pulses (Kawashima and Shoji, 2000; Abdel Raheem, 2009; Zhu et al., 2004). However, all the mentioned studies were carried out on isolated highway bridges or isolated buildings using the uniform ground motion. Detailed investigations on the multi-frame bridges subjected to spatially varying ground motions were not reported. Also none of the above studies investigated the use of rubber bumper along with the SMA restrainers.

This paper presents few results from an investigation carried out on the effectiveness of combining rubber bumper with SMA or steel restrainers on multi-span bridge frames to mitigate the localised damages caused by pounding and unseating subjected to spatially varying ground motions (Shrestha et al., 2013). The study focuses on the so called balanced frames which are emphasized by the prevailing codes as a method to mitigate relative displacement-related damages such as pounding and unseating. A comparison on the effectiveness of the above mentioned devices on mitigating the response of bridge structures in combination and or acting alone are presented. Based on the numerical results, conclusions on the effectiveness of rubber bumpers with restraining devices to mitigate pounding and unseating damage are drawn.

2. NUMERICAL MODEL

Two typical Californian Highway Bridges with five spans are selected for the analysis. The expansion joints on the bridges are located nearly at the inflection points (i.e., 1/4 to 1/5 of span). The bridge deck consists of box-type girders with pre-stressed concrete. The bridge details are described in Feng et al. (2000) and Kim et al. (2000). Two 2-D nonlinear finite element models as shown in Fig. 1 are developed for the analysis, which represent

- Model Bridge 1H: a five-span bridge with one expansion joint and equal column height of 19.83 m.
- Model Bridge 2H: a five-span bridge with two expansion joints and equal column height of 19.83 m.

The geometry and the boundary conditions of these bridge models are shown in Fig. 1. The bridge models are developed in the nonlinear software package Seismostruct (2012). Concrete bents are modelled by inelastic force based reinforced concrete beam column elements. Reinforced concrete sections are constructed from three materials, namely unconfined concrete, confined concrete and reinforcing steel. The superstructure of the bridge is modelled using the elastic beam-column elements. Elastomeric bearings consisting of an elastomeric rubber pad are modelled by the elastic perfectly plastic element to represent the frictional force developed at elastomeric pad. In this study the coefficient of friction, μ, between the deck and bearing is taken as 0.36. The yield force and yield displacement of the lumped bearings are assumed to be 896.4 kN and 33.87 mm respectively. Abutments are modelled by two separate nonlinear springs representing the pile stiffness and passive soil stiffness at abutment. The nonlinear abutment behaviour in this study reflects the design recommendation from Caltrans (Caltrans 1990, Caltrans 2010). The Pier foundation is assumed to be fixed and soil structure interaction is neglected.

With the given properties of the two bridges, the natural periods of the bridge segments is calculated based on an Eigen value analysis. Natural periods of the target bridge segments and the ratio of their fundamental periods are presented in Table 1. The ratios of fundamental natural periods of both the bridge models are above 0.7 (i.e. $T_i/T_j \geq 0.7$, where T_i is the natural period of stiffer frame and T_j is the natural period of flexible frame). Thus both the considered bridge models meet the design guide of the balanced frame geometry, recommended by the code as a method to mitigate large pounding impact as well as the unseating damage (Caltrans 2010).

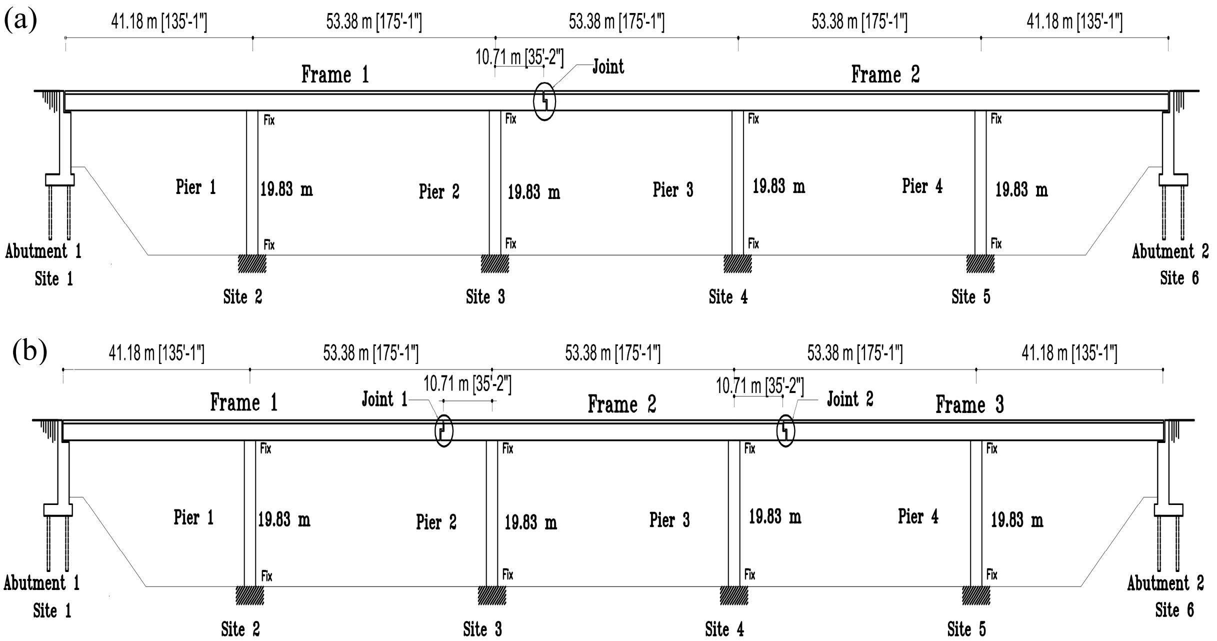

Fig. 1. Bridge Models used for the study (a) Model 1 with single intermediate hinge, (b) Model 2 with two intermediate hinges

Table 1. Natural periods of model bridges

Bridge Model	Stiffer frame period (T_i, sec)	Flexible frame period (T_j, sec)	Period ratio (T_i/T_j)
Model 1	0.84 (Frame 1)	0.92(Frame 2)	0.91
Model 2	0.75 (Frame 2)	1.04 (Frame 1 & 3)	0.72

Two types of restrainers are investigated in this study, i.e., the steel and SMA restrainers. Steel cable restrainers are modelled by using the tension only bilinear elements. The length of the restrainers is fixed to 5.04m thus limiting the relative displacement to 88 mm within the elastic range of the restrainer. The yield stress of the restrainers is 1210 MPa and initial modulus of elasticity is 69000 MPa. The initial stiffness of the restrainers of 30 kN/mm and strain hardening of 5% are assumed. The initial slack of the cables is assumed to be 15 mm. SMA restraining devices which are composed of the bundled or twisted SMA wires in the form of the cables are modelled using the uni-axial model for super-elastic SMA, programmed by Fugazza (2003), and that follows the constitutive relationship proposed by Auricchio and Sacco (1997). This model is capable of reproducing both super elasticity and damping properties of SMA. A typical stress-strain relationship of SMA is illustrated in Fig. 2(a). The initial slack of the SMA cables are also assumed to be 15mm. To compare the effectiveness of the SMA cables with steel cable restrainers, the effective stiffness of the SMA device at the elastic strain limit (7% strain) is assumed to be equal to the initial stiffness of the designed steel strain (1.75% strain) to ensure both the devices will experience same force at their extreme elastic strain levels. This can be achieved by using a shorter SMA cable of 1.26m. Fig. 2b compares the hysteretic behaviour for the super elastic SMA device with the steel restrainers' hysteretic behaviour.

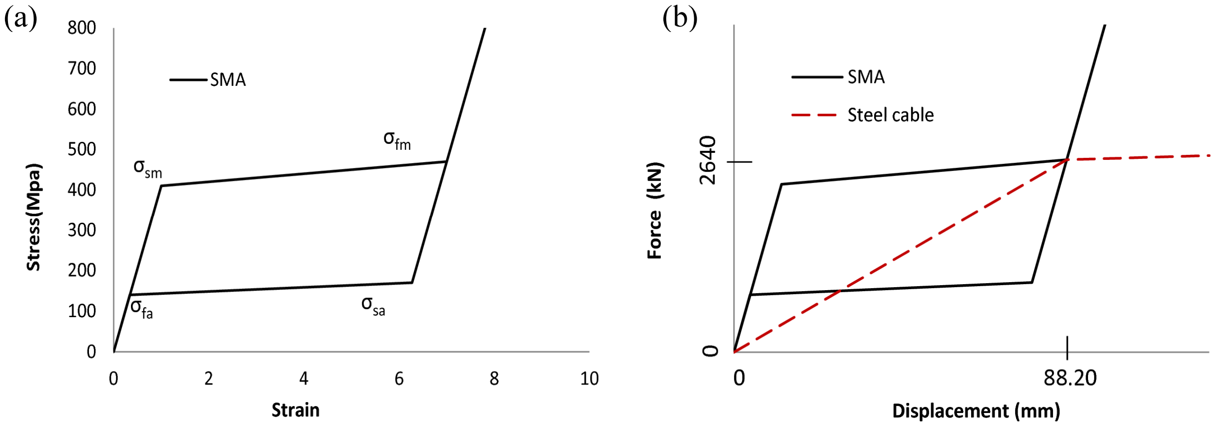

Fig. 2. (a) Constitutive modelling of SMA based restrainers; (b) Force displacement relationship of steel cable restrainers and SMA based restrainers

It is recognized that the pounding can affect the response of the bridge and hence must be considered in the seismic analysis. A common way of implementing this phenomenon is by using the contact element in the finite element model of the bridge. Essentially the element monitors the gap between the adjacent sections of the bridge and is activated once the associated gap is closed. The spring stiffness, K_i, is proportional to the axial stiffness of the neighbouring structural segment (Kawashima and Shoji, 2000; Abdel Raheem, 2009). The stiffness of the linear impact element, which activates after the gap closing, is given by:

$$K_i = \gamma \frac{AE}{L} \qquad (1)$$

where E, A and L are the properties of the surrounding girders. In this study the stiffness of the gap element, $Ki = 3.6\text{x}10^7$ kN/m is taken, resulting in value of constant γ nearly equal to 20 and 14 for bridge model 1 and 2, respectively. To mitigate the large pounding forces rubber bumper are proposed to be placed at the in-span hinges to act as shock absorbers, as shown in Fig. 3(a). In this study the constitutive model of the linear strain hardening rubber bumpers are based on the study of Kawashima and shoji (2000). 10 rubber bumpers of 250mm x 150mm section and 50mm thick are used between the decks. The initial stiffness of the rubber bumper is taken to be 12.5 KN/mm. A multi-linear strain hardening model, as presented in Fig. 3(b), is used in the study with second stiffness branch of 12 times of the first stiffness branch and third stiffness branch of 24 times of the first stiffness branch followed by the stiffness K_i. Previous researches concluded that energy dissipation in the shock absorbing device is less significant on the response of the structure and the maximum pounding impacts (Kawashima and Shoji, 2000; Polycarpou and Komodromos, 2011). The energy dissipation of both the impact element and the rubber bumper is thus neglected in this study.

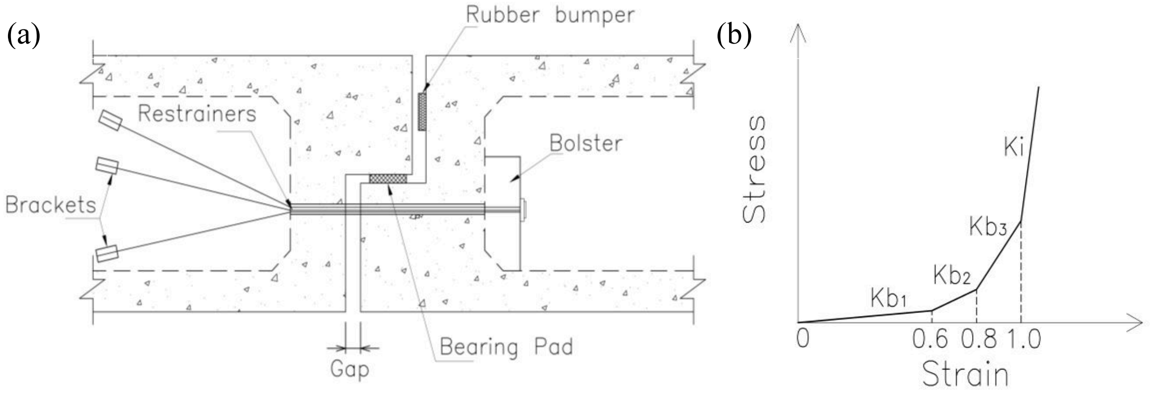

Fig. 3. (a) Schematic figure of expansion joint with bumper and restrainers; (b) Stress strain relationship of impact element including the rubber bumper.

3. GROUND MOTION MODELING

It is common in engineering practice to simulate spatially varying ground motions that are compatible with the specific design response spectra. Many stochastic ground motion simulation methods have been proposed by different researchers. For example, Hao et al. (1989) and Deodatis (1996) simulated the spatially varying ground motions in two steps: first the spatially varying ground motion time histories are generated using an arbitrary power spectral density function, and then adjusted through iterations to match the target response spectrum. Usually a few iterations are needed to achieve a reasonable good match. More recently, Bi and Hao (2012) further developed this method by simulating the spatially varying ground motions which are compatible with the ground motion power spectral densities that are related to the target design response spectra instead of arbitrary power spectral density functions. Compared with the methods suggested by Hao et al. (1989) and Deodatis (1996), less or even no iterations are needed in the latter approach (Bi and Hao, 2012), the latter method is thus computationally more efficient. The method proposed by Bi and Hao (2012) is adopted in the present study to simulate the spatially varying ground motion time histories that are compatible with the design spectra specified in the New Zealand Earthquake Loading Code (2004).

The spatial variation properties between ground motions recorded at two locations j and k on ground surface is modelled by an empirical coherency loss function (Sobczky, 1991).

$$\gamma_{jk}(i\omega) = \left|\gamma_{jk}(i\omega)\right| \exp(-i\omega d_{jk} \cos\alpha / v_{app}) = \exp(-\beta\omega d_{jk}^2 / v_{app}) \cdot \exp(-i\omega d_{jk} \cos\alpha / v_{app}) \qquad (2)$$

where β is a constant reflecting the level of coherency loss, and $\beta = 0.0002$ is used in the present study. d_{jk} is the distance between the two locations j and k in the wave propagation direction, f is the frequency in Hz, v_{app} is the apparent wave velocity, and α is the seismic wave incident angle. In the present study, v_{app} is assumed to be 400 m/s, and $\alpha = 60^\circ$. The simulated acceleration time histories are based on the response spectra for shallow soil site condition specified in the New Zealand Earthquake Loading Standard normalized to 0.72g and 5% damping.

4. NUMERICAL RESULT

4.1 EFFECTS OF SPATIALLY VARYING GROUND MOTION

Three sets of simulated spatially varying ground motions compatible with the soft soil spectrum of the New Zealand Earthquake Loading Standard are applied to investigate the effects of spatial ground motion on the response of model bridges. The responses of the bridges in terms of joint opening and pounding force at in-span hinges are compared. The ground motion time history simulated for site 1 is applied to all the sites for the uniform ground motion case. To quantity the amplification on the response of the bridge structures by ground motion spatial variation, an amplification factor, α is used. The amplification factor, α is defined as the ratio of the bridge response with spatially varying ground motion to the response with uniform ground motion. Fig. 4(a) shows the pounding and joint opening response amplification for joint of bridge model 1 and Fig. 4(b) shows the same for the joint 2 of the bridge model 2. The result shows that for the bridge 1 pounding forces can be amplified by as much as 2.47 times and joint opening can increase by 15.10 times compared to uniform ground excitation. For joint 2 of the bridge model 2 the pounding forces are amplified by 2.02 times and joint opening increases by 9.47 times compared to the uniform motion. The result presented indicates spatially varying ground motions lead to the out-of-phase motion of the adjacent structures that could result in significantly large relative displacement and pounding force for the structures with close fundamental periods. This clearly indicates that adjusting the fundamental period of the adjacent structures close to each other is not sufficient to mitigate the pounding damage and the unseating failure when spatial variation of the ground motion is considered.

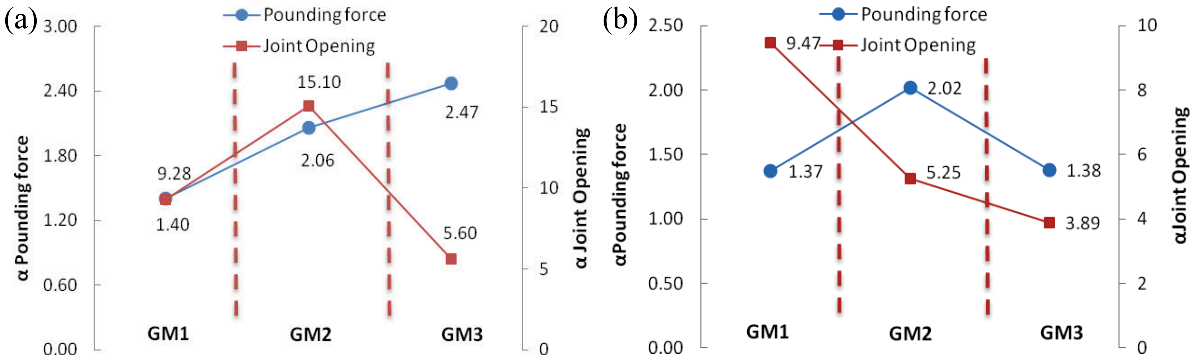

Fig. 4. (a) Response amplification at in-span joint of bridge model 1; (b) Response amplification at joint 2 of bridge model 2

4.2 RESPONSE WITH MITIGATING DEVICES

Poundings between adjacent bridge structures with limited gap sizes provided by conventional expansion joints are unavoidable. Pounding results in large impact forces and transfers large lateral force from one deck to another. Such large impact forces and large lateral force transfer could result in localised damages in decks and abutments or even the collapse of the bridge spans. Using a layer of soft visco-elastic material as a shock absorbing media between the decks of the bridge along with the restraining device could mitigate large impact force and unseating damages. A simple and inexpensive method of placing a rubber bumper between decks of the bridge could be an effective method for eliminating large impact forces, and hence eliminating the large acceleration pulses caused due to the impacts.

In this study a series of analyses are conducted to investigate the effectiveness of natural rubber bumpers along with the restrainers to mitigate large amplitude impacts and unseating damage. Six different models are investigated to examine the effect of addition of natural rubber bumpers with and without the restrainers (Steel cable and SMA) on the responses of the bridge structures. The rubber bumpers of thickness of 50mm are provided in the 100mm expansion joints of two bridge models. Fig. 5 compares the pounding forces time-history at mid-span hinges of the bridge model 1 with and without rubber bumpers. Inclusion of rubber bumper as a shock absorbing device results in a reduction of the pounding forces, but leads to more number of poundings due to reduction of the gap width. Using rubber bumper also elongates duration of pounding. Fig. 6 shows the acceleration responses of the deck at impact location. As shown, incorporation of rubber bumpers eliminates acceleration spikes. Fig. 7 shows the peak impact force and opening relative displacement at the joint of the bridge model 1 subjected to the three sets of ground motions for soft soil condition (GM1 to GM3), in which AB and RUB represent the bridge models as built and with rubber bumpers, RES and RES+RUB represent the case of bridge models with steel restrainers and steel restrainers with rubber bumpers, respectively; and SMA and SMA+RUB represent the case of bridge models with SMA restrainers alone and with rubber bumpers. As shown inclusion of rubber bumpers not only affects the impact force, but also the relative opening displacement between the adjacent decks. This is because rubber bumper changes the impact force as well as reduces the separation gap between the adjacent decks, which may results in either increase or decrease of the relative separation displacement.

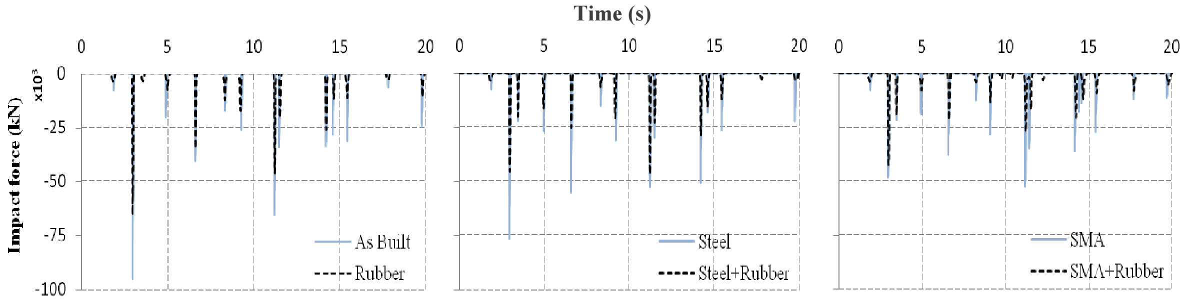

Fig. 5. Pounding forces time history at the joint of bridge model 1 with and without rubber bumper for a set of spatially varying ground motions.

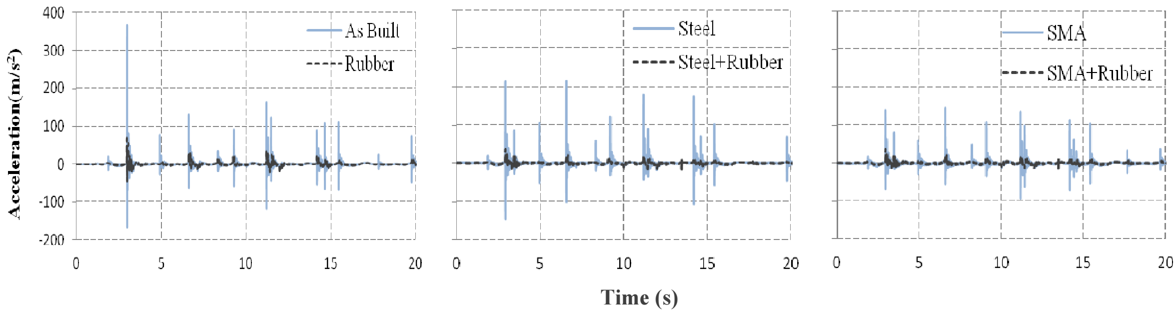

Fig. 6. Joint acceleration time history at the joint of bridge model 1 with and without rubber bumper for a set of spatially varying ground motions.

Fig. 8 depicts the peak impact force and the maximum opening displacement at joint 2 of the bridge model 2 corresponding to the different sets of motions and mitigation conditions. As shown, the application of rubber bumpers alleviates the peak impact forces. However, the effects of the rubber bumpers on the relative separation response of the bridge joints are not always beneficial. Inclusion of rubber bumpers may result in a larger joint opening displacement because of the more number of impacts and prolonged impact duration, hence may lead to an increased unseating damage potential especially in bridges with multiple joints. Therefore it is important to use rubber bumpers together with restrainers to mitigating pounding damage while preventing deck unseating. Comparing the responses of bridge joints presented in Figs. 7 and 8, it can be summarized that SMA based restrainers combined with rubber bumpers could significantly improve the responses of bridge joints by not only reducing the relative joint opening but also the peak pounding forces.

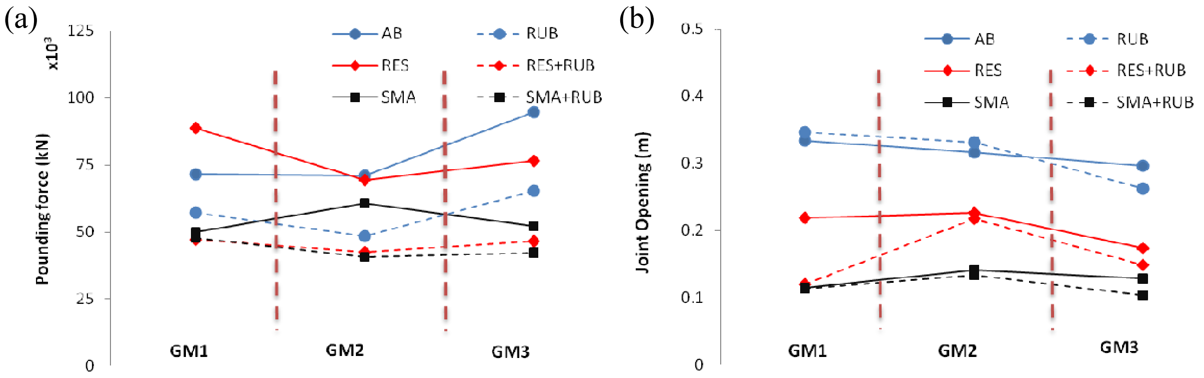

Fig. 7. Comparison of (a) the maximum pounding force and (b) the maximum relative joint opening with and without rubber bumpers for bridge model 1

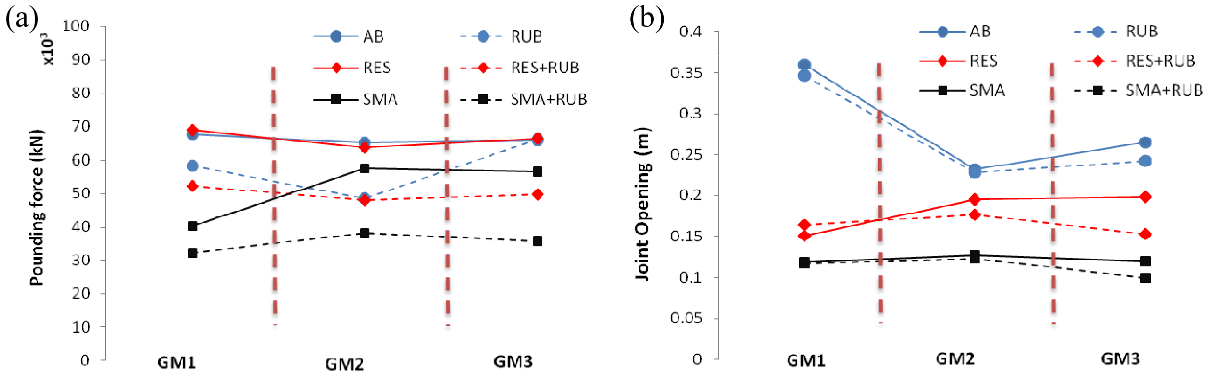

Fig. 8. Comparison of (a) the maximum pounding force and (b) the maximum joint opening with and without rubber bumpers for joint 2 of bridge model 2

5. CONCLUSION

The paper presents numerical studies on relative displacement responses of adjacent bridge structures with close fundamental periods to spatially varying ground motions. The results presented suggest that the bridges are subjected to larger pounding force and relative joint opening due to differential support motions; thus adjusting the fundamental periods of adjacent bridge frames close to each other is not sufficient to mitigate the pounding related damages. The study presented also shows that using restrainers combined with the rubber bumper could be an effective method of reducing the large pounding forces and preventing unseating damage. Rubber bumper also shows high effectiveness in eliminating the large acceleration spikes but results in more numbers of poundings due to the reduction of the gap width and increases the duration of the impact. The results suggest that use of SMA restrainers and the rubber bumper together at bridge expansion joints could be the most effective in mitigating the damaging impact as well as the large separation between the adjacent structures.

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REFRENCES

Abdel Raheem, SE. (2009) Pounding mitigation and unseating prevention at expansion joints of isolated multi-span bridges, Engineering Structures, Vol 31, No 10, pp 2345-56.

Andrawes, B. and DesRoches, R., (2005) Unseating prevention for multiple frames bridges using super elastic devices. Smart Mat and Struct, Vol 14, No 3, pp 60-67.

Auricchio, F. and Sacco, E., (1997) A super elastic shape-memory alloy beam. Jour of Int mat and Struct, Vol 8, pp 489-501.

Bi, K. and Hao, H., (2012) Modelling and simulation of spatially varying earthquake ground motions at sites with varying conditions, Prob Eng Mech, Vol 29, pp 92-104.

Bi, K. and Hao, H., (2013) Numerical simulation of pounding damage to bridge structures under spatially varying ground motions, Engineering Structures, Vol 46, pp 62-76.

Caltrans. (1990) Seismic Design Criteria. Design manual-first edition, California Dept. of Transportation, Sacramento, CA.

Caltrans. (2010) Seismic Design Criteria. Design manual-version 1.6, California Dept. of Transportation, Sacramento, CA.

Chouw, N. and Hao, H., (2008) Significance of SSI and non-uniform near-fault ground motions in bridge response I: Effect on response with conventional expansion joint, Engineering Structures, Vol 30, No 1, pp 141-53.

Chouw, N. and Hao, H., (2005) Study of SSI and non-uniform ground motion effects on pounding between bridge girders. Soil Dyn & Earthquake Eng, Vol 23, No7, pp 717-28.

Chouw, N. and Hong, H., (2012) Pounding Damage to Buildings and Bridges in the 22 February 2011 Christchurch Earthquake. Int Jour of Protective Struct, Vol 3, No 2, pp 123-140.

Comartin, C. Greene, M. and Tubbesing, S., (1995) The Hyogo-Ken Nanbu Earthquake Preliminary Reconnaissance Report, EERI, Oakland, CA.

DesRoches, R. and Delemont, M., (2002) Seismic retrofit of simply supported bridges using shape memory alloys, Engineering Structures, Vol 24, No 3, pp 325-32.

Deodatis, G., (1996) Non-stationary stochastic vector processes: seismic ground motion applications. Prob Eng Mech, Vol 11, No 3, pp 149-167.

Feng, MQ. Kim, JM. Shinozuka, M. and Purusinghe, R., (2000) Viscoelastic dampers at expansion joints for seismic protection of bridges. Jour of Bridge Eng, Vol 5, No 1, pp 67-74.

Fugazza D., (2003) Shape-memory alloy devices for earthquake engineering: Mechanical properties, constitutive modeling and numerical simulations. Master's Thesis, University of Pavia, Italy.

Guo, A. Qingjie, Z. and Li, H., (2012) Experimental study of a highway bridge with shape memory alloy restrainer focusing on the mitigation of unseating and pounding. Earthquake Eng & Eng Vib, Vol 11, No 2, pp 195-204.

Hao, H. Oliveira, CS. and Penzien J., (1989) Multiple-station ground motion processing and simulation based on SMART-1 Array data. Nuc Eng & Design, Vol 111, pp 293-310.

Kawashima, K. and Shoji, G., (2000) Effect of Restrainers to Mitigate Pounding between Adjacent Decks to a Strong Ground Motion, 12th WCEE, Auckland, New Zealand, paper no. 1435.

Kawashima, K. Takahashi, Y. Hanbin, G. Wu, Z. and Zhang, J., (2009) Reconnaissance Report on Damages of Bridges in 2008 Wenchuan, China, Earthquake, Jour of Earthquake Eng, Vol 13, No 7, pp 965-996.

Kawashima, K. Unjoh, S. Hoshikuma, J. and Kosa, K., (2011) Damages of Bridges due to the 2010 Maule, Chile, Earthquake. Journal of Earthquake Eng, Vol 15, No 7, pp 1036-1068.

Kim JM, Feng MQ, Shinozuka M. Energy dissipating restrainers for highway bridges. Soil Dynamics and Earthquake Engineering 2000; 19 (1): 65-69.

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

Moehle, JP.,ed., (1995) Northridge Earthquake of January 17, 1994: Reconnaisance Report No. UCSD/SSRP-93/05, Structural Systems Research Project, University of California, San Diego, Lalloa, CA.

Padgett, JE. DesRoches, R. Ehlinger, R., (2010) Experimental response modification of a four span bridge retrofit with shape memory alloys. Struct Control & Health Moni, Vol 17, No 6, pp 694-708.

Polycarpou, PC. and Komodromos. P., (2011) Numerical investigation of potential mitigation measures for poundings of seismically isolated buildings. Earthquake & Struct, Vol 2, No 1, pp 1-24.

Saiidi, M. Margakis, E. Adbel-Ghaffar, S. and O'Conner, D., (1993) Response of bridges hinge restrainer during earthquakes-field performance, analysis and design. Report CCEER 93/06. Reno: Center for Civil Eng Earthquake Res, University of Nevada.

Seismosoft Inc. Seismo-struct user Manual for version 6; 2012.

Selna, LG. Malvar, LJ. and Zelinski, RJ., (1989) Bridge retrofit testing: Hinge cable restrainers, Jour of Struct Eng, Vol 155, No 4, pp 950-34.

Shrestha, B. Hao, H. and Bi K., (2013) Effectiveness of using Rubber bumper and Restrainer on mitigating pounding and unseating damage of Bridge structures subjected to spatially varying ground motions, Engineering structures, (Revision submitted).

Sobczky, K. (1991) Stochastic Wave Propagation. Kluwer Academic Publishers, Netherlands.

Standards New Zealand. (2004) Structural design actions, Part 5, Earthquake actions in New Zealand (NZS1170.5-2004).

Zhu, P. Abe, M. and Fujino, Y., (2004) Evaluation of Pounding countermeasures and Serviceability of Elevated Bridges during Seismic excitation using 3D modelling, Earthquake Eng & Struct Dyn, Vol 33, No 5, pp 591-609.