INNOVATIVE CONTROL STRATEGY FOR SEISMIC POUNDING MITIGATION OF BRIDGE STRUCTURES

Shehata E. Abdel Raheem[1] and T. Hayashikawa[2]

[1] *Lecturer of Structural Engineering, Civil Engineering Department, Faculty of Engineering,, Assiut University, Assiut, EGYPT*
[2] *Professor, Bridge and Structural Design Engineering, Graduate school of Engineering, Hokkaido University, Sapporo, JAPAN*
Email: shehataraheem@yahoo.com, toshiroh@eng.hokudai.ac.jp

ABSTRACT :

Damages of adjacent bridge structures due to relative responses such as poundings and unseating have been observed in many earthquakes. The isolators in bridge structures are effective in mitigating the induced seismic forces, however, the deck displacement becomes excessively large when subjected to a ground motion with unexpected characteristics, therefore increase the possibility of pounding; contribute to the unseating of bridge decks and subsequent collapse. An analytical model of expansion joints that takes account of the interaction between adjacent segments of the bridge deck and the effect of impact and restrainers is developed for nonlinear time history analysis. The numerical results show that pounding between adjacent bridge segments could amplify the relative displacement, resulting in the requirement of a longer seat width to support the deck. Pounding results in a transfer of large lateral force from a deck to the other, consequently, results in significant changes in the global response of the participating structural systems. So it is effective to provide a shock absorber between adjacent decks for the mitigation of pounding effect.

KEYWORDS: Pounding mitigation, Expansion joint, Seismic design, Bridge, Shock absorber, Unseating prevention, Restrainers.

1. INTRODUCTION

Due to lack of structural redundancy bridges receive severe damage and generally lead to catastrophic failures during earthquakes. For the bridges with relatively short piers, the natural frequency of vibration lies in the range of pre-dominant frequencies of the earthquake ground motions, particularly when founded on rock or hard soil. Merely increasing the strength of members will not be effective and uneconomical too, unless the transmission of the earthquake forces and energy into the structure is reduced. Therefore, base isolation devices may replace the conventional bridge bearings; Seismic isolation is an innovative earthquake resistant design approach that introduces flexibility at the isolation level and supplying means of energy dissipation. Such isolation devices decouple the bridge deck from bridge substructure during earthquakes, consequently reducing the forces transmitted to abutments and piers. Thus, the bridge is protected against damage from the earthquake by limiting the earthquake attack rather than resisting it [1 ~ 3]. Expansion joint may be a weak point in an isolated bridge where large relative displacement occurs between decks, the relative displacement anticipated at an expansion joint in a standard bridge under a design ground motion could reach many times of the standard clearance between decks. Such large relative displacements between the adjacent girders can not only cause poundings but also their unseating and subsequent collapse. Pounding between adjacent bridge segments could amplify the relative displacement, resulting in the requirement of a longer seat width to support the deck [4 ~ 5]. Damages of adjacent bridge structures due to relative responses such as poundings and unseating have been observed in many earthquakes in the past, e.g. during the 1994 Northridge earthquake [6], the 1995 Kobe earthquake [3], and the 1999 Chi-Chi earthquake [7]. Pounding of adjacent superstructure segments in highway bridges during severe earthquakes can result in significant structural damage. Although pounding causes only local damage at the contact face, it transfers large seismic lateral forces from one deck to another, which results in a significant change in the seismic response of the entire bridge system. It is not well known yet how the pounding will affect the unseating of the bridge girders. Investigations of pounding and unseating prevention devices effects on the total response of a bridge system are therefore important to avoid pounding and unseating of bridge decks, it is favorable to mitigate the pounding effect [8 ~ 12].

This study investigates how potential poundings of adjacent segments of isolated bridges affects the effectiveness of seismic isolation, practical measures are suggested to mitigate the negative effects of earthquake induced poundings of seismically isolated bridges. Parameter studies are conducted to determine the effects of frequency ratio, gap size, restrainers' configuration, substructure flexibility at expansion joint and ground motions on the bridge seismic response. The analysis is conducted on a two-dimensional structural component model of an isolated highway bridge. The results show that the influence of pounding on the structural response is significant in the longitudinal direction of the bridge and depends on the frequency ratio and gap size between superstructure segments. Further analysis indicates that the bridge behavior can be effectively improved by placing rubber pads between bridge segments and at both ends of restrainers, acceleration response spikes caused by forces at expansion joint by impact and stretching of cable restrainers between adjacent segments of bridge could be significantly reduced by using rubber shock absorbing device.

2. NONLINEAR FINITE ELEMENT MODEL FORMULATION

The analysis on the bridge model is conducted using an analytical method based on the elastoplastic finite displacement dynamic response analysis; where geometric and material nonlinearities are taken into account. Based on the total incremental equilibrium equations, elastoplastic finite displacement analysis could be formulated, the tangent stiffness matrix and nodal point force vectors considering both geometrical and material nonlinearities can be determined by using the fiber model in which the bending-axial force interaction is automatically considered. The initial state of residual stresses effects on both tangent stiffness and force vector is considered. Elastoplastic finite displacement analysis could be formulated as follow

$$[\mathbf{K_T}]_e \{\Delta u\}_e = \{\Delta f\}_e \tag{1}$$

$$[\mathbf{K_T}]_e = [\mathbf{K_{ep}}]_e + [\mathbf{K_\sigma}]_e = \int_v [\mathbf{B_1}]^T [\mathbf{D_{ep}}][\mathbf{B_1}]dv + \int_v [\mathbf{B_2}]^T [\boldsymbol{\sigma}][\mathbf{B_2}]dv \tag{2}$$

in which $[\mathbf{K}_T]_e$, $[\mathbf{K}_{ep}]_e$ and $[\mathbf{K}_\sigma]_e$ = tangent, elastoplastic and initial stress matrices; $\{\Delta u\}_e$ and $\{\Delta f\}_e$ = incremental displacement and force vectors of the element, respectively; $[\mathbf{B}_1]$ and $[\mathbf{B}_2]$ = matrices of interpolation functions; $[\boldsymbol{\sigma}]$ and $[\mathbf{D}_{ep}]$ = initial stress and elastoplastic material constant matrices. In the nonlinear incremental analysis, the structure tangent stiffness matrix, which is assembled from the element tangent stiffness matrices, is used to predict the next incremental displacements under a loading increment.
In order to obtain the natural frequencies and vibration modes of the bridge model, the eigenproblem is solved

$$[\mathbf{K}_0]\varphi = \omega^2 [\mathbf{M}]\varphi \tag{3}$$

where $[\mathbf{K}_0]$ is the initial stiffness matrix; $[\mathbf{M}]$ is the common consistent mass matrix; φ and ω are mode shape and the corresponding circular frequency.
The analysis on the bridge model is conducted using an analytical method based on the elastoplastic finite displacement dynamic response analysis. The governing non-linear equation of motion can be derived by the principle of energy in which the external work is absorbed by the work of internal, inertial and damping forces for any small admissible motion that satisfies compatibility and essential boundary conditions [13 ~ 14]. Hence, the incremental finite element dynamic equilibrium equation at time $t+\Delta t$ over all the elements can be expressed written as follow:

$$[\mathrm{M}]\{\ddot{u}\}^{t+\Delta t} + [\mathrm{C}]\{\dot{u}\}^{t+\Delta t} + [\mathrm{K}]^{t+\Delta t}\{\Delta u\}^{t+\Delta t} = -[\mathrm{M}]\{\ddot{z}\}^{t+\Delta t} \tag{4}$$

where $[\mathrm{M}]$, $[\mathrm{C}]$ and $[\mathrm{K}]^{t+\Delta t}$ represent respectively the mass, damping and tangent stiffness matrices of the bridge structure at time $t+\Delta t$; while $\ddot{u}$, $\dot{u}$, u and $\ddot{z}$ denote the structural accelerations, velocities, incremental displacements and earthquake accelerations at time $t+\Delta t$, respectively. The incremental equation of motion accounts for both geometrical and material non-linearities. Material non-linearity is introduced through the bilinear elastic-plastic stress-strain relationship of the beam-column element, incorporating a uniaxial yield criterion and kinematic strain-hardening rule. The yield stress is 353 MPa, the elastic modulus is 200 GPa and the strain hardening in plastic area is 0.01. Newmark's step-by-step method of constant acceleration is formulated for the integration of the equation of motion. Newmark's integration parameters ($\gamma = 0.25, \beta = 0.5$) are selected to give the required integration stability and optimal result accuracy. The equation of motion is solved for the incremental displacement using the Newton-Raphson iteration scheme where the stiffness matrix is updated at each increment to consider geometrical and material non-linearities and to speed the convergence rate. The damping mechanism is introduced in the analysis through the Rayleigh damping matrix. The particular values of damping coefficients are set to ensure a 2% inherent modal damping for the first two natural modes of the bridge structure.

3. ANALYTICAL MODEL OF TARGET BRIDGE STRUCTURE

3.1 Bridge Model

A typical highway bridge consisting of 3-spans and two adjacent segments frame-bridge as shown in Fig.1 is analyzed. The superstructure is of steel plate girder with 40 m span and 12m wide and the steel piers are 12 m high, total weight of a 3-span bridge is 20.2 MN. An analytical model of the bridge is defined in order to represent effectively the global structural response. The bridge is idealized as a two-dimensional nonlinear numerical finite element model; the dynamic response analysis is conducted for the bridge longitudinal direction. Base isolation with Lead Rubber Bearings (LRBs) is considered to passively reduce seismic responses of the bridge. The design shear force level for the yielding of lead plugs is taken to be 0.10M, where M is the part of the deck weight carried by bearings [14, 15]. The shear degree of freedom for all the isolation bearings are modeled by a bilinear model and based on three parameters, namely initial stiffness; post-yield stiffness and characteristic strength. Based on an eigenvalue analysis of the target bridge using a two-dimensional finite element model, natural period of the system of the left segment and that of the right segment based on the effective stiffness of the LRB bearings and its period ratio are calculated. Different configurations of cable restrainers are considered to limit relative displacement, as shown in Fig. 2. The restrainers would typically be used in a tension-only manner, with a thermal gap provided to limit the engaging of the restrainers during thermal cycles. Shock absorber of rubber pads between bridge segments and at both ends of restrainers are used to improve the bridge behavior and reduce the negative effect of sudden impact pulses through smooth change of impact stiffness and stretching the cable restrainers between adjacent segments of the bridge.

3.2 Expansion Joint Analytical Model

Because the characteristics of expansion joints have a major influence on the seismic response of bridge structures, they must be correctly modeled. The existence of the gap introduces nonlinearity into the seismic analysis of the structure. Shock absorbers and/or restrainers between the adjacent girders is a popular way to overcome problems associated with the pounding in highway bridges [8], the effects of pounding are reduced by absorbing the energy of the impact by installing shock absorbers, Fig. 2. Restrainers, a kind of device installed to prevent unseating of girders, can also benefit the reduction of the pounding effects [1, 16]. Schematic of bridge expansion joint with various restrainers configuration is shown in Fig. 2, an analytical model of

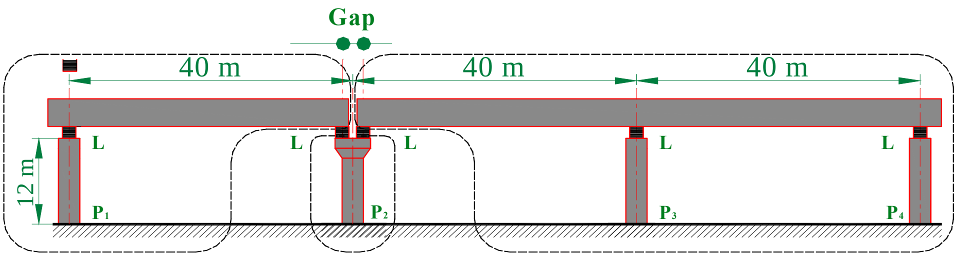


Fig. 1 Base isolated bridge model with LRB bearings (L)

expansion joints that takes account of the effect of pounding and restrainers is developed. The external nodes of adjacent segments were linked by nonlinear gap elements to model the impact forces resulting from collision. The force-deflection characteristics of such elements are shown in Fig. 3. The spring stiffness, K_I, is fixed equivalent to the axial stiffness of the neighboring structural segments [16], the stiffness is expressed as

$$K_I = \gamma EA / L \tag{5}$$

Where; EA is stiffness of axial cross section of superstructure, L is the length of the member of superstructure and γ is the ratio of impact spring stiffness to stiffness of superstructure. The stiffness of the impact spring is equal to 9.8 MN/m; various values of the gap between two decks are assumed to investigate the gap size effects. Cable restrainers are often used at expansion joint as a retrofit measure to limit relative displacement and prevent unseating during an earthquake. However, the presence of restrainers alters the behavior of adjacent frames by transferring forces as the frame opening exceeds the slack in the cable. The restrainers are modeled as tension-only springs with a slack, three restrainers configuration are considered: configuration I through expansion joint, the restrainers are connected from deck to deck; configuration II through pier, the restrainers are connected from pier cap to the bottom flange of the girder beam, while configuration III considers shear key with configuration I as shown in Fig. 2. A potential practical measure to alleviate the detrimental effects of poundings could be the installation of flexible material that would protrude at certain locations of a seismically isolated bridge, where poundings are expected. The suggested collision shock absorbers can simply be rubber

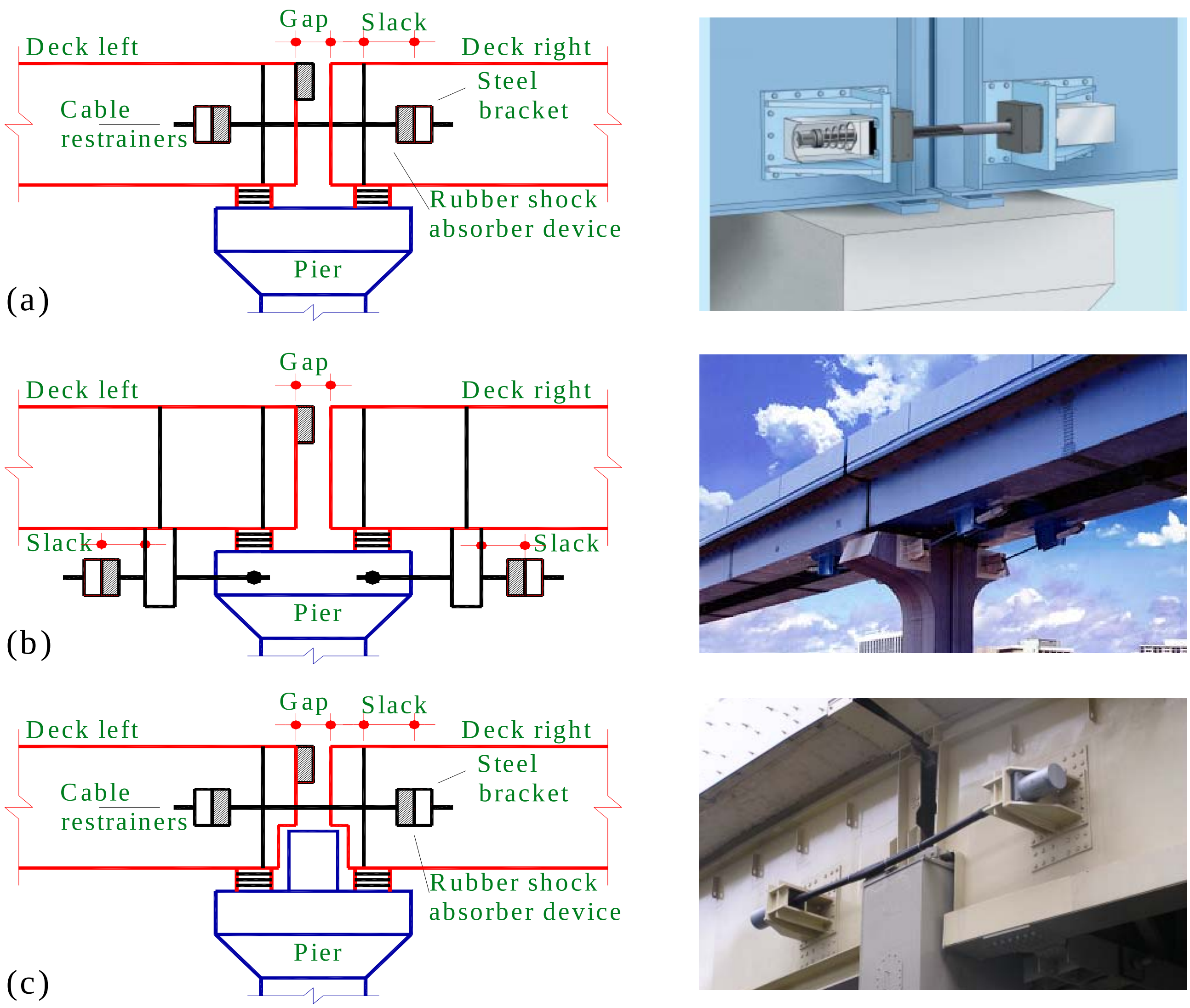


Fig. 2 *Schematic of bridge expansion joint with various restrainers configurations: (a) through the hinge – Configuration I, (b) through the pier – Configuration II,(c) through hinge with shear key – Configuration III*

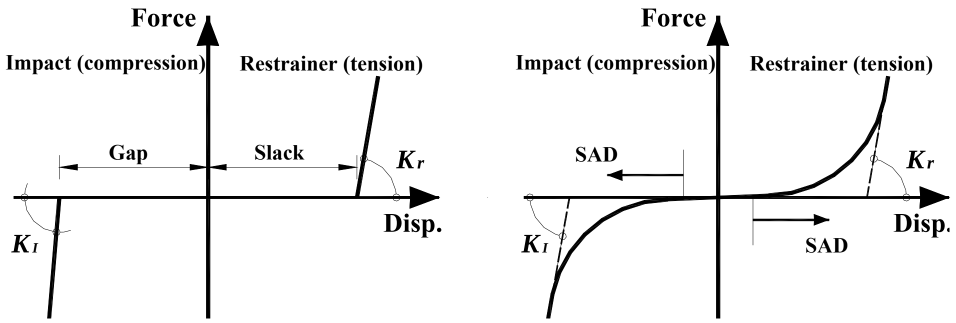
pads attached to the adjacent decks end and at ends of restrainers. Their presence can make the changes of the stiffness during poundings smoother and, therefore, prevent, to some extent, the acceleration spikes due to sudden impact pulses.

3.3 Input Ground Motions

Owing to severe damage to many bridges caused by the 1995 Hyogo-ken Nanbu Earthquake, very high ground motion (level II design) is now required in the new Japanese bridge design specification set in 1996, in addition to the relatively frequent earthquake motion (level I design) by which old structures were designed and constructed. Level II earthquake data has Type I (inter-plate) and Type II (intra-plate). Three representative ground motions generated by an inland earthquake at short distance and recorded in the 1995 Kobe earthquake considered in the analysis, are the standard earthquake motions recommended by Japan Road Association as Level 2; Type II for moderate soil. The response spectrums for damping ratio 0.05 are shown in Fig. 4.

4. NUMERICAL RESULTS AND DISCUSSION

The model of a base isolated highway bridge specified according to the Manual for Menshin Design of Highway Bridges [16 -18] is used to study the influence of pounding on structural response and practical measures are suggested to mitigate the negative effects of earthquake induced poundings. The finite element models for nonlinear seismic pounding analysis are built, and the influence of different parameters on the seismic pounding responses of the bridges is analyzed. Parameter studies are conducted to determine the effects of frequency ratio, gap size, restrainers' configuration and ground motions on the pounding response of the bridge. The isolated bridge model with the fundamental frequency ratio of 0.74 (Model I) and 0.52 (Model II) of the two adjacent bridge structures is considered. The fundamental frequency of the left bridge frame (stiff) with an assumed fixed base is kept constant at 0.96 Hz while the fundamental frequency of the right bridge frame (flexible) bridge frame has been varied for two different frequencies of 0.71 and 0.50 Hz. The LRB bearings are modeled with a bilinear element with strain hardening. An impact element is used to model pounding between the decks in the



(a) w/o shock absorber *(b) with shock absorber*

Fig. 3 *Pounding, restrainers and shock absorber device (SAD) models*

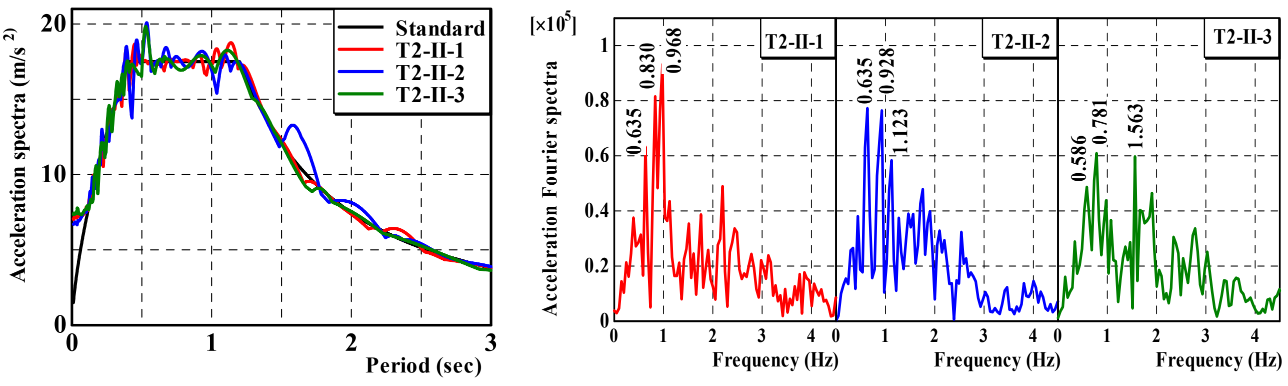


Fig. 4 Acceleration response spectra of the earthquake motions

bridge; the compression gap element has springs that penalize closing of the gap, the restrainers are modeled as tension-only springs with a slack. For detailed investigation of the interaction between adjacent segments of bridge, a wide range of gap size from 0.05 to 0.25 m with increment of 0.05 m is used to investigate gape size effect on bridge response and compared to no-pounding case, a critical separation gap (G) of 0.10 m has been selected to study the restrainers configuration and shock absorber effects; the cable restrainers are given initial slack (S) of 0.10 m (configurations I & III) and 0.20 m (configuration II) to allow relative movement during temperature variations. Five cases are investigated in this study to determine the different parameters effects:

- Case I: The reference case of bridge model response without pounding;
- Case II: The bridge model with pounding;
- Case III: The bridge model with pounding and restrainers through hinge (Configuration I)
- Case IV: The bridge model with pounding and restrainers through pier (Configuration II)
- Case V: The bridge model with pounding and restrainers through hinge with shear key (Configuration III)

4.1 Pounding Effects between Adjacent Decks

The relative displacement at the expansion joint and the adjacent bridge segments displacement determine the effect of poundings and restrainers. Based on the bridge model, The peak values of stiff and flexible frame segments displacement and its relative response, Fig. 5 for different gape size show that the pounding reduces the segment displacement response when vibrating near the characteristic period of the ground motion and increase the adjacent segment response, Moreover, the relative displacement at expansion joint is driven by the flexible segment response, this effect is more significant for model II with highly out-of-phase frame segments. The displacement time histories of the analyzed superstructure segment for gap 0.1 m (Case II) together with the response when no pounding (Case I) occurs are presented; a positive relative displacement of the expansion joint corresponds to an opening of the joint gap (outward) while a negative relative displacement corresponds to a closing (inward), the results indicate that pounding can significantly alter the behavior of the structure depending on gap size, frequency ratio and input earthquake wave characteristics as shown in Fig. 6. Seismic pounding, generates high magnitude and short duration acceleration pulses that can cause structural damage. The impact force and acceleration response amplification depend on the gap size ratio to the relative displacement of Case I, the frequency ratio, the frame segment fundamental frequency relative to that of ground motion. The pounding of adjacent frames could transfer the seismic demand from one frame to the next, which can be detrimental to the standalone capacity of the frame receiving the additional seismic demand. The unbalanced distribution of pounding forces found across the expansion joint is able to cause local damage to colliding girders and transmit high impact forces to bearing supports and substructures. The results of different gap size for case II, show that for two gap size intervals between adjacent superstructure segments, the smallest structural response can be obtained, the optimal gap size is either a very small one or large enough to avoid collisions. The interval of a very small gap size stands for the case of nearly fully continuous deck. On the other hand, in the case of a large gap size, every superstructure segment vibrates independently and the energy is dissipated through its free movement. Nevertheless, in order to prevent collisions, a significant increase of the separation gap would be required. However, enlarging the gap between superstructure segments leads to large expansion joint and disturbs traffic on the deck

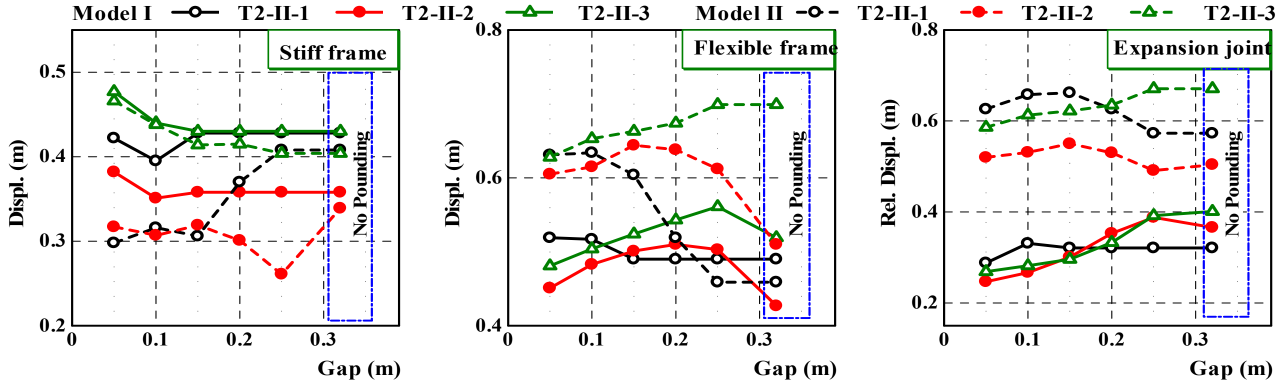


Fig. 5 Displacement peak response time history

4.2 Restrainers Configuration Effects

It is well known that under an extreme excitation, the unseating prevention devices are effective to maintain the integrity of a total bridge system. It prevents an excessive relative displacement between decks or between a deck and substructure and even prevent drop of a deck that dislodges from its support. Variety of unseating prevention devices such as cable restrainers, a connection of adjacent decks and a connection of a deck to a substructure have been used worldwide. Restrainers that connect deck to deck, configuration I perform effectively to minimize the possibility of deck unseating and reduce the pounding forces at the expansion joint for bridge with conventional bearings, where a deck with movable bearing is connected to a deck on the other side of expansion joint with fixed bearing. Special attention should be paid to the base isolation bearing in the expansion join details, the restrainers could ensure a significant reduction of the relative separation displacement and also the impact force due to poundings is significantly decreased; the relative displacements between the superstructure and substructure at both left and right LRBs are slightly reduced as shown in Fig. 7. Hence configuration I of restrainers is not effective for unseating prevention for isolated bridges but it could secure

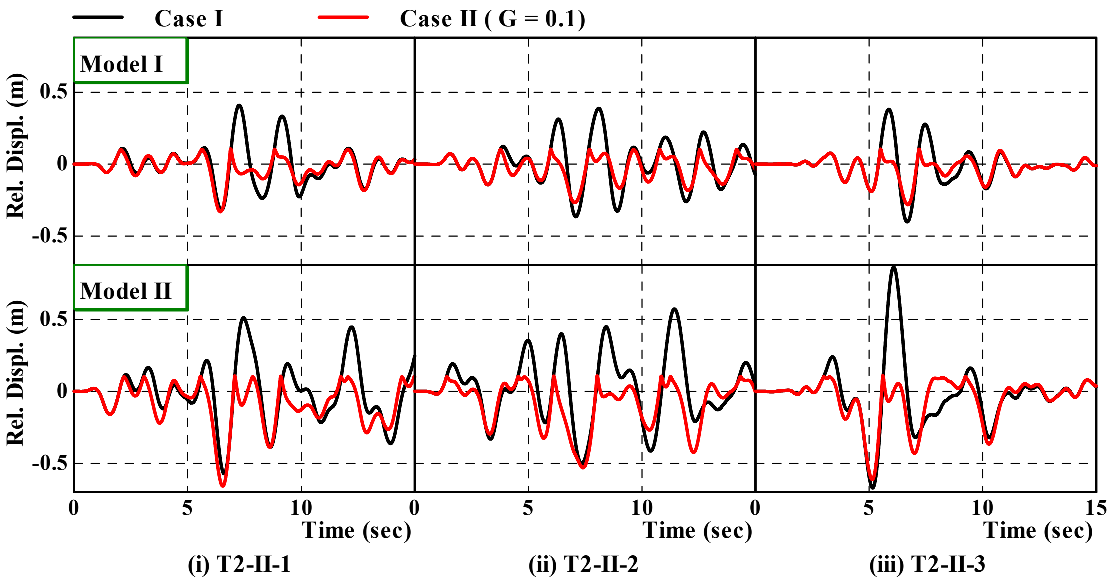


Fig. 6 Expansion joint relative displacement response time history

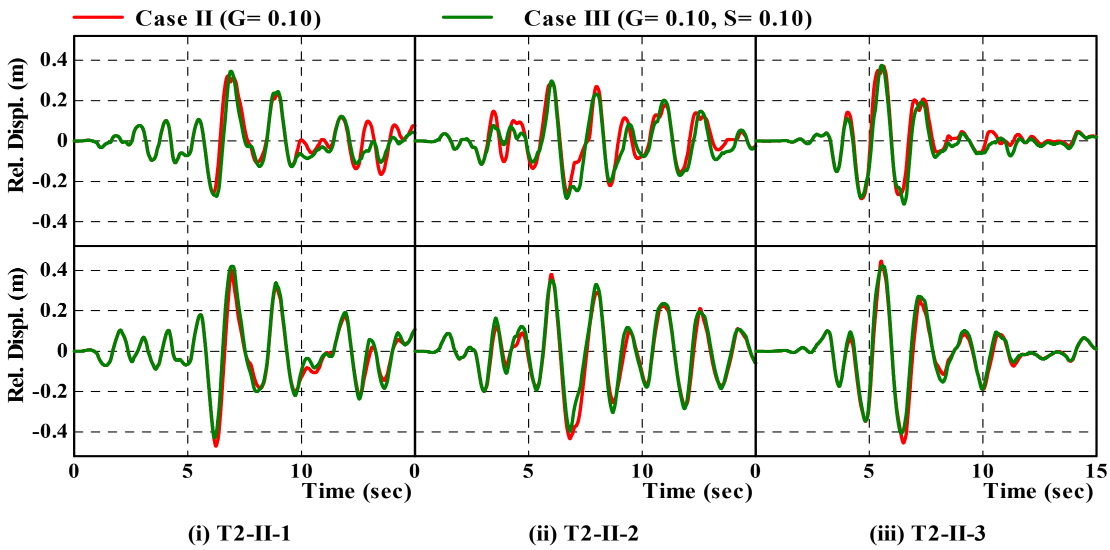


Fig. 7 Relative displacement time history at LRB level

falling prevention. However, Restrainers through pier, configuration II and through hinge with shear key, configuration III could effectively restrict the displacements between the superstructure and substructure, hence reduce the possibility of unseating, moreover the closing and separation relative displacement is significantly reduced but on the expense of the seismic force demand of the supporting pier at the expansion joint.

Table 1 presents selected average peak values of the response of the isolated bridge under three standard design earthquake excitations, the maximum separation displacement is significantly reduced due to pounding (Case II); while the deck displacement and acceleration of both stiff and flexible frame segments are significantly amplified. The pounding could amplify/de-amplify the relative displacement between two bridge segments, to withstand the effect of pounding, a longer seat width should be provided to support a deck. The pounding and relative displacement of adjacent frames will transfer the seismic demand from one frame to the next, which can be detrimental to the standalone capacity of the frame receiving the additional seismic demand. The results for cases III ~ V demonstrate the effect of using restrainers in different configuration on the bridge seismic responses. The restrainers through hinge (Case III) could effectively reduce the effect of pounding on expansion joint opening deformation and impact force by around 47% and 38%, respectively. Also the acceleration response of neighbours stiff and flexible frame segments is significantly reduced, but the relative displacement at LRB level (Unseating displacement) is slightly affected even sometimes it could be amplified that could increase the risk of the unseating of the bridge decks. The restrainers with configuration II and III (cases IV and Case V) could control the expansion joint opening deformation and secure the unseating of the bridge decks on the expense of the increase of shear and moment seismic demand of the supporting pier at the expansion joint, which should carefully redesign.

Table 1 Model I peak response under real earthquake excitations

Seismic response		Average (T2-II-1, T2-II-2, T2-II-3)				
		Case I	Case II	Case III	Case IV	Case V
Closing displacement (*m*)		0.393	0.105	0.103	0.104	0.104
Separation displacement (*m*)		0.363	0.293	0.156	0.161	0.207
Impact force (*MN*)		--	45.75	28.04	35.14	35.31
Expansion joint supporting pier shear (*MN*)		4.79	4.81	4.98	11.01	12.20
Expansion joint supporting pier Bending Moment (*MN.m*)		95.42	94.96	100.47	217.36	239.30
Stiff frame (left)	Unseating displacement (m)	0.299	0.268	0.290	0.234	0.205
	Deck displacement (*m*)	0.405	0.395	0.419	0.418	0.454
	Deck acceleration (m/s^2)	9.49	114.03	73.97	89.61*	115.23
	Shear force (*MN*)	2.51	2.53	2.53	2.66	2.70
	Bending moment (*MN.m*)	49.97	49.12	50.80	52.15	54.22
Flexible frame (right)	Unseating displacement (m)	0.450	0.409	0.398	0.360	0.208
	Deck displacement (*m*)	0.498	0.501	0.477	0.513	0.494
	Deck acceleration (m/s^2)	8.37	121.27	80.62	102.29*	112.83
	Shear force (*MN*)	3.17	3.28	3.25	3.42	3.27
	Bending moment (*MN.m*)	62.92	63.55	62.44	67.55	63.89

4.3 Shock Absorber for Mitigation of Pounding Effects

Since poundings between adjacent decks are unavoidable in an isolated bridge, this effect has to be carefully included in design. Poundings results in a transfer of large lateral force from a deck to the other, no matter how the damage of a deck as a direct result of pounding is localized and limited, this results in damage in piers and bearings in the other deck. Consequently it is effective to provide a shock absorber between adjacent decks and at the restrainers ends for the mitigation of pounding effect. The analysis results indicate that reaction forces at the piers bases and pounding forces exerted on the superstructure can be satisfactorily reduced by applying simple method of placing rubber shock absorber between bridge segments or at the restrainers' ends as potential practical mitigation measures against impact due to poundings and stretching of the restrainers, by that way, the sudden changes of the stiffness during poundings can be smoothed and therefore prevent, to some extent, the acceleration peaks due to impacts.

The effects of a natural rubber shock absorber on isolated bridge model response are investigated for the studied cases. Figs. 8 and 9 compare response of the bridge model with and without the shock absorbers. In the bridge without the shock absorbers, pounding occurred once resulting in a large impact force; this caused pulse acceleration with high magnitude spikes at the end of the decks. On the other hand, in the bridge with the shock absorbers, the peak pounding force decreased resulting in the decrease of deck acceleration. Installation of the shock absorbing device significantly reduces the force between the decks generated at expansion joint due to impact and stretching of cable restrainers; hence reduce the acceleration response spikes. When the expansion joint undergoes an increasing relative movement in the positive direction, the rubber pad first deforms under compression action providing resistance to the motion, when the separation relative movement reaches the cable restrainers slack, the restrainers begin to resist further opening of the joint gap. This resistance builds up

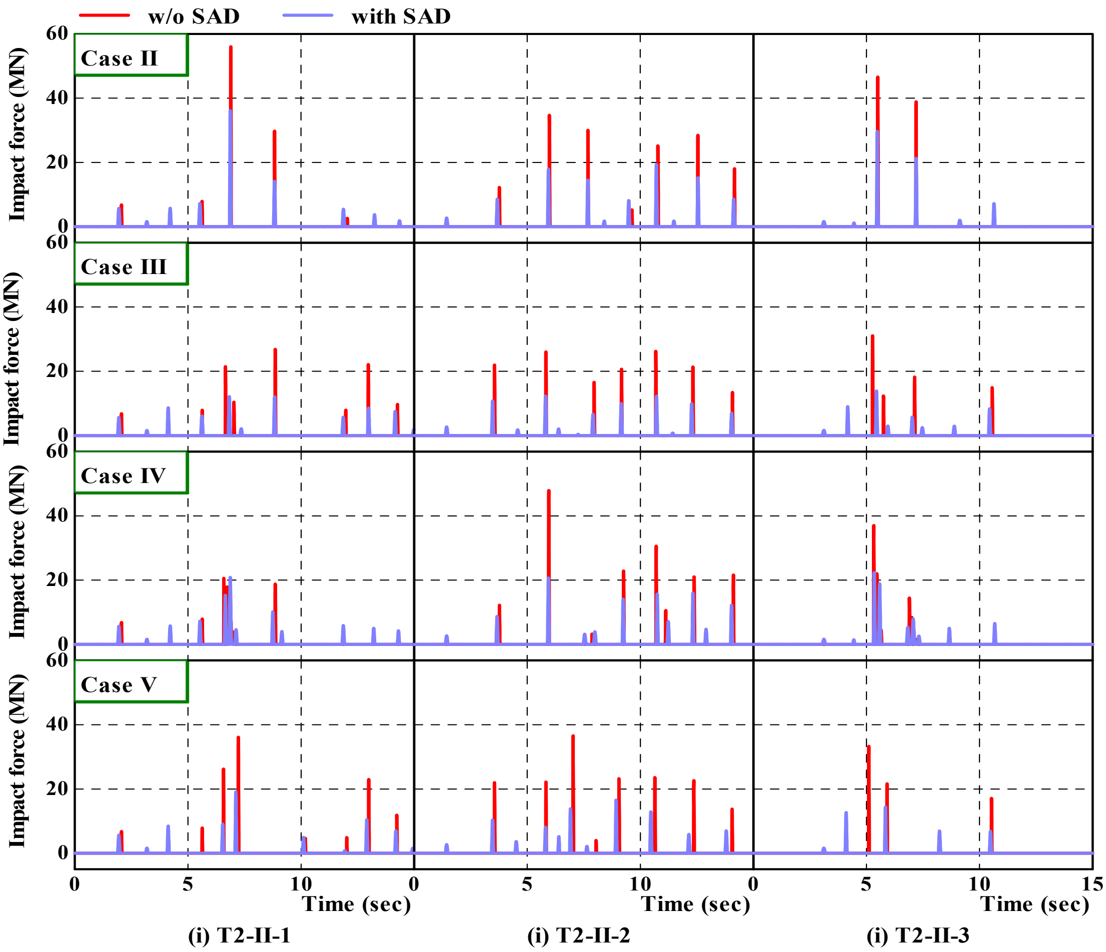


Fig. 8 Impact force time history response with/without SAD

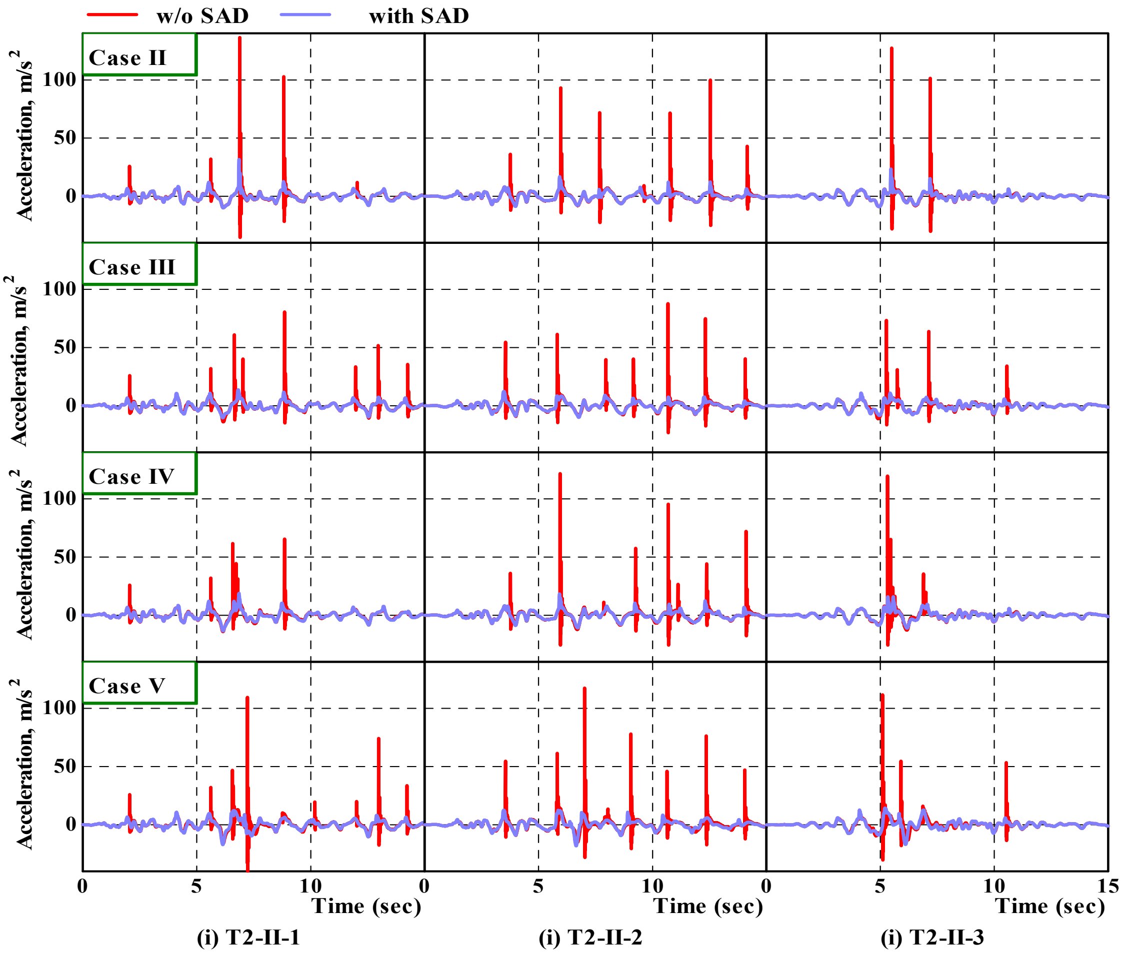


Fig. 9 Deck acceleration time history response with/without SAD

nonlinearly with joint separation, with smooth stiffness change. When the expansion joint undergoes a relative movement in the relative closing direction, the rubber pad deforms and resists the motion in the same manner described above for the positive direction. The interaction between the adjacent segments occurs by both pounding and engagement of the cable restrainers. The installation of a shock absorber could reduce the required cable restrainers' force; hence more economical design could be achieved.

5. CONCLUSIONS

In this study, the effects of poundings on seismically isolated bridges during strong earthquakes are investigated in an effort to gain insight into this complicated problem, an analytical simulation by nonlinear dynamic response analysis is conducted and control measures for the seismic pounding responses of the highway bridges are investigated. The finite element models for nonlinear seismic pounding analysis are built, and the influence of different parameters on the seismic pounding responses of the highway bridges is analyzed, which include the effects of frequency ratio, gap size, restrainers' configuration and slack and input ground motion characteristics. The simulations results indicate that the effectiveness of seismic isolation could be significantly affected from potential poundings when the provided seismic gap is exceeded. The interaction between adjacent bridge segments occurred by both impacts and the engagement of the cable restrainers that tie together adjacent segments. Seismic pounding, generates high magnitude and short duration acceleration pulses that can result in severe impact forces that damage structural members like the deck or pier. Furthermore, seismic pounding can amplify the global response of the participating structural systems. The influence of pounding on the structural behavior is significant in the longitudinal direction of the bridge and depends much on the gap size between superstructure segments relative to the separation displacement of the model without pounding and input excitation characteristics. The smallest structural response can be obtained for very small gap sizes and for gap sizes large enough to avoid collisions. However, the application of both intervals is usually an undesirable solution.

Under an extreme excitation, the unseating prevention devices are effective to maintain the integrity of a total bridge system. It prevents an excessive relative displacement between decks and even prevent drop of a deck that dislodges from its support. The pounding could amplify the relative displacement between two bridge segments, to withstand the effect of pounding, a longer seat width should be provided to support a deck. The pounding of adjacent frames will transfer the seismic demand from one frame to the next, which can be detrimental to the stand alone capacity of the frame receiving the additional seismic demand. Configuration I of restrainers connecting deck to deck is not effective for unseating prevention for isolated bridges but it could secure falling prevention. However, Restrainers through pier, configuration II and through hinge with shear key, configuration III could control the expansion joint opening deformation and secure the unseating of the bridge decks on the expense of the increase of shear and moment seismic demand of the supporting pier at the expansion joint, which should carefully redesign.

Further analysis indicates that reaction forces at the piers bases and pounding forces exerted on the superstructure can be satisfactorily reduced by applying simple method of placing rubber shock absorber between bridge segments or at the restrainers' ends. The sudden changes of the stiffness during poundings can be smoothed through using natural rubber shock absorber installed at deck ends and/or restrainers end, and therefore prevent, to some extent, the acceleration peaks due to impacts. Installation of the shock absorbing device significantly reduces the force between the decks generated at expansion joint due to impact and stretching of cable restrainers. The rubber shock absorbing device with half gap/slack size provides economical and effective design that could reduce the impact force and acceleration response.

REFERENCES

[1] JAPAN ROAD ASSOCIATION, Specification for Highway Bridges - Part V Seismic Design, Maruzen, Tokyo, 1996.

[2] JAPAN ROAD ASSOCIATION, Reference for Highway Bridge Design, Specification for Highway Bridges-Part IV Substructures, 1996.

[3] COMMITTEE OF EARTHQUAKE ENGINEERING, The 1995 Hyogoken-Nanbu Earthquake, Investigation into Damage to Civil Engineering Structures, Japan Society of Civil Engineers, 1996.

[4] HAYASHIKAWA T., HIROOKA T., IKEDA K. and ABDEL RAHEEM S.E., "Dynamic behaviour of viaducts with PC cables in consideration of pounding of girders and energy absorption", *Proceedings of Hokkaido Chapter of the Japan Society of Civil Engineer*s, *JSCE*, Vol. 59, 2003, pp. 50-53.

[5] RUANGRASSAMEE A. and KAWASHIMA K., "Relative displacement response spectra with pounding effect", *Earthquake Engineering and Structural Dynamics",* Vol. 30, 2001, pp. 1511–1538.

[6] MOEHLE J.P., "Northridge earthquake of January 17, 1994: Reconnaissance report. Volume 1–Highway bridges and traffic management", *Earthquake Spectra*, Vol. 11 (C), 1995, pp. 287–372.

[7] HAMADA M., NAKAMURA S., OHSUMI T., MEGRO K. and WANG E, editors, "The 1999 Ji-Ji earthquake, Taiwan-investigation into damage to civil engineering structure", *Japan Society of Civil Engineering*, JSCE, 1999, pp. 160.

[8] JANKOWSKI R., WILDE K. and FUJINO Y., "Reduction of pounding effects in elevated bridges during earthquakes", *Earthquake Engineering and Structural Dynamics*, Vol. 29, 2000, pp. 195-212.

[9] ZHU P., ABE M. and FUJINO Y., "Evaluation of pounding countermeasures and serviceability of elevated bridges during seismic excitation using 3D modeling", *Earthquake Engineering and Structural Dynamics*, Vol. 33, 2004, pp. 591-609.

[10] DESROCHES R. and MUTHUKUMAR S., "Effect of pounding and restrainers on seismic response of

multiple-frame bridges", *Journal of Structural Engineering, ASCE,* Vol. 128(7), 2002, pp. 860-869.

[11] DESROCHES R, FENVES G.L., "Design of seismic cable hinge restrainers for bridges", *Journal of Structural Engineering, ASCE,* Vol. 126(4), 2000, pp. 500-509.

[12] TAKENO S., OHNO H. and IZUNO K., "Velocity-based design of seismic unseating prevention cable and shock absorber for bridges", *Structural Engineering and Earthquake Engineering*, *JSCE*, Vol. 21(2), 2004, pp. 175-188.

[13] ABDEL RAHEEM S.E. and HAYASHIKAWA T., "Parametric study on steel tower seismic response of cable-stayed bridges under great earthquake ground motion", *JSCE Structural Engineering and Earthquake Engineering*, Vol. 20(1), 2003, pp. 25-41.

[14] ALI H.M. and ABDEL-GHAFFAR A.M., "Modeling the nonlinear seismic behaviour of cable-stayed bridges with passive control bearings", *Computers & Structures*, Vol. 54, No. 3, 1995, pp. 461-492.

[15] ROBINSON W.H., "Lead rubber hysteretic bearings suitable for protecting structures during earthquakes", *Earthquake Engineering and Structural Dynamics*, Vol. 10, 1982, pp. 593-604.

[16] KAWASHIMA K. and SHOJI G., "Effect of restrainers to mitigate pounding between adjacent decks subjected to a strong ground motion", *Proceedings of 12th World Conference on Earthquake Engineering-12WCEE*, Auckland, New Zealand, 31 January – 4 February 2000, Paper No. 1435.

[17] JANKOWSKI R., WILDE K. and FUJINO Y., "Pounding of superstructure segments in isolated elevated bridge during earthquakes", *Earthquake Engineering and Structural Dynamics*, Vol. 27, 1998, pp. 487-502.

[18] ABDEL RAHEEM S.E. and HAYASHIKAWA T., "Control strategy for seismic pounding mitigation of bridge structures", *International Association for Bridge and Structural Engineering–IABSE*, *Information and Communication Technology (ICT) for Bridges, Buildings and Construction Practice*, Helsinki, Finland, June 4-6, 2008, CD-ROM, Paper ID. B35, 2008.