MITIGATION MEASURES FOR EXPANSION JOINT EFFECTS ON SEISMIC PERFORMANCE OF BRIDGE STRUCTURES

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ABSTRACT

Investigations into past and recent earthquake damages have illustrated that the multiple-frame bridge and the multi-span simply supported bridge are most susceptible to pounding damage at expansion joints due to numerous independent components and lack of continuity in the bridge structure. So this study objective is development of analytical model and methodology for the formulation of the pounding problem to evaluate the structural pounding effects on the bridges global response; to determine proper seismic hazard mitigation practice for already existing as well as new bridge structures and to provide engineers with practical analytical tools for predicting seismic response and damage. The analysis results show that the variation of vibration properties of two adjacent bridge components is a dominant factor causing differential displacements when the natural frequencies of the two components differ from each other noticeably. Pounding can amplify the bridge displacement demands beyond those typically assumed in design. The pounding structure response is reduced significantly with increase in effective damping through implementing energy dissipating system

Keywords: Expansion joint, restrainers, seismic pounding, shock absorber, unseating prevention

1. INTRODUCTION

Through numerous field observations after damaging earthquakes and previous analytical and numerical studies [1-4], pounding has been identified as the primary cause for the initiation of collapse, damage of adjacent superstructures segments in bridges due to relative responses such as poundings and unseating have been observed in many earthquakes in the past, e.g. 2011 Tohoku earthquake [5], during the 1994 Northridge earthquake [6], the 1995 Kobe earthquake [7], and the 1999 Chi-Chi earthquake [8]. **Figure 1a** and **b** shows the pounding damage between the adjacent bridge girders and between the bridge girder and the abutment of Santa Clara River Bridge in 1994 Northridge earthquake owing to the gaps at the expansion joints cannot accommodate the closing

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relative displacements [6]. Unseating damage can occur when the opening relative displacement exceeds the seating length, and this is especially a problem in older construction when bridges were usually designed with short seats. **Figure 1c** and **d** show the unseating damage at Changgan Bridge during 1999 Chi–Chi earthquake [8] and at bridge spans at TEM overpass during 1999, Kocaeli earthquake [9].

Pounding causes local damage at the contact face, moreover, 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 and the base isolation system efficiency. Investigations of pounding and unseating prevention devices effects on bridge system response are therefore important to avoid pounding and unseating of bridge decks, moreover, it is favorable to mitigate the pounding and unseating effect [10-13]. Expansion joints are weak point in an isolated bridge where a large relative displacement occurs, the relative displacement anticipated at an expansion joint in a standard bridge under a design earthquake could reach many times of the standard decks clearance. Pounding between adjacent bridge segments could amplify the relative displacement, resulting in the requirement of a longer seat width to support the deck [14-15]. So this study objective is the development of analytical model and methodology for the formulation of the problem based on the classical impact theory to evaluate the structural pounding effects on the bridges global response; to determine proper seismic hazard mitigation practice for already existing as well as new bridge structures and to provide engineers with practical analytical tools for predicting pounding response and damage.

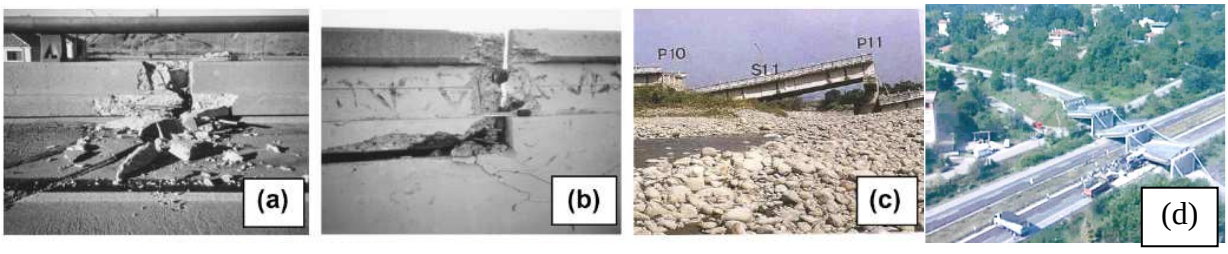

Figure 1 Typical seismic induced earthquake damages (a and b) pounding damage, (c and d) unseating damage

2. FINITE ELEMENT FORMULATION

The analysis on the bridge model is conducted using an analytical method based on the elastoplastic finite displacement dynamic response analysis. 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. Material nonlinearity 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 motion equation. The equation of motion is solved for the incremental displacement using the Newton-Raphson iteration scheme, the damping mechanism is introduced through the Rayleigh damping matrix. The damping coefficients are set to ensure 2% inherent modal damping for the first two natural modes of the bridge.

3. NUMERICAL FINITE ELEMENT MODELS

3.1. Target Bridge Numerical Model

A typical highway bridge consisting of 3-spans and two adjacent segments frame-bridge as shown in **Figure 2** is analyzed. The superstructure is of steel plate girder with 40 m span and 12 m 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. Cross sectional properties of the deck and the bridge piers are summarized in **Table 1**. Base isolation with Lead Rubber Bearings (LRBs) is considered to passively reduce seismic responses of the bridge. The shear degree of freedom for all the isolation bearings is modeled by a bilinear model. a parametric analysis has been performed in order to obtain the optimal values of the yielding forces and the post-yield stiffness by considering as objective function the moments of the piers, the displacement of the deck and energy dissipation. The principal parameters that characterize LRB analytical model are the pre-yield stiffness K_1, corresponding to combined stiffness of the rubber bearing and the lead core, the stiffness of the rubber K_2 and the yield force of the lead core F_y, given in **Table 2**.

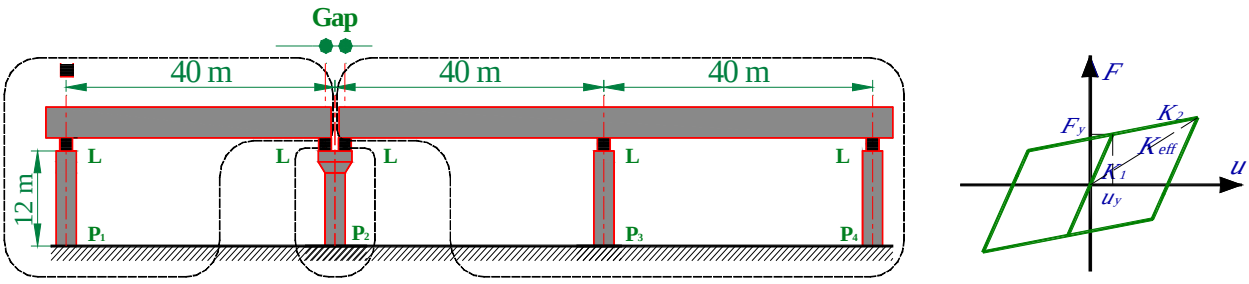

Figure 2 Base isolated bridge model with LRB bearings (L)

Table 1 Cross section properties of piers and deck

Structure component	Area, A (m^2)	Moment of inertia, I (m^4)	Torsion constant, J (m^4)
P_1, P_4	0.39	0.2473	0.3707
P_2, P_3	0.92	0.8127	1.2167
Deck	1.16	0.8199	1.8934

Table 2 LRB base isolation system parameters

LRB parameters location	K_1 (MN/m)	K_2 (MN/m)	F_y (MN)
P_1 , $P_2{}^l$	66.15	6.615	0.662
$P_2{}^r$, P_4	44.10	4.410	0.441
P_3	58.80	5.880	0.588

Different configurations of cable restrainers as pounding countermeasures and unseating prevention system are considered to limit relative displacement at expansion joint, as shown in **Figure 3**. 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 bridge segments.

3.2. Expansion Joint Model

Schematic of bridge expansion joint with various restrainers configuration is shown in **Figure 3**, an analytical model of 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-deformation characteristics of such elements are shown in **Figure 4**. The spring stiffness, K_I, is fixed equivalent to the axial stiffness of the neighboring structural segments [13, 16-18], the stiffness is expressed as:

$$K_I = \gamma EA / L \tag{3}$$

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, in this study, γ is taken equal to 2 through sensitivity analysis of impact element stiffness. The stiffness of the impact spring is taken equal to 9.8 GN/m.

Figure 3 Schematic of 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

Cable restrainers are often used at expansion joint as a retrofit measure to limit relative displacement and prevent unseating during an earthquake. The restrainers are modeled as tension-only springs with a slack, three restrainers configurations 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. A potential practical measure to alleviate the detrimental effects of impact due to poundings and stretching of restrainers could be the installation of flexible material that would protrude at certain locations of a seismically isolated bridge. The suggested collision shock absorbers can simply be rubber pads attached to the adjacent decks end and at ends of restrainers.

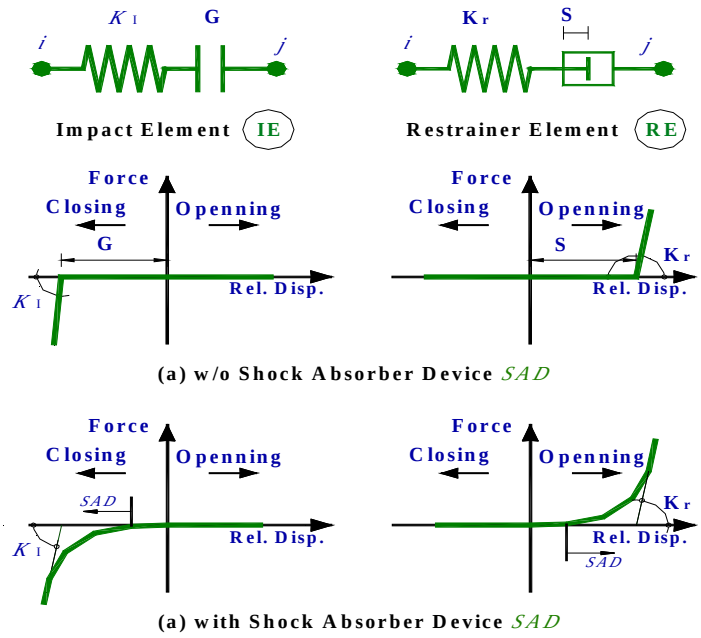

Figure 4 Pounding, restrainers and shock absorber device (*SAD*) analysis models

3.3. Selected Input Earthquake 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 [7, 19-20]. 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. In addition to two representative ground motion records are used in the analysis.

4. NUMERICAL RESULTS AND DISCUSSION

The model of a base isolated highway bridge specified according to the Manual for Menshin Design of Highway Bridges 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. Parametric 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 frequency ratio of 0.74 of the two adjacent bridge segments is considered. The fundamental frequency of the left bridge frame (stiff) and right bridge frame (flexible) with an assumed fixed base are taken equal to 0.96 and 0.71 Hz, respectively. 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 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 installation of cable restrainers with clearance length allows the thermal and shrinkage movement and restrainers are activated when the relative displacement between adjacent vibrating units exceeds specified clearance length. The clearance length of a restrainer is 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: bridge model with pounding;
Case III: bridge model with pounding and restrainers through hinge (Configuration I)
Case IV: bridge model with pounding and restrainers through pier (Configuration II)
Case V: bridge model with pounding and restrainers through hinge / shear key (Configuration III)

4.1. Pounding between Adjacent Decks Effects on Bridge Seismic Response

The relative displacement at the expansion joint and the adjacent bridge segments displacement determine the effect of poundings and restrainers. Based on the bridge models, the peak responses values of stiff and flexible frame segments displacement and its relative response, **Figure 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 with highly out-of-phase frame segments. The displacement response of the segment which has a longer natural period dominates over the displacement response of the segment with a shorter natural period, making the displacement closer to that of the segment with a longer natural period. 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. 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. At the pounding instant, the flexible structure will push the stiffer structure away. As a consequence of this, the flexible structure experiences less vibration, and the stiffer structure suffers stronger oscillation.

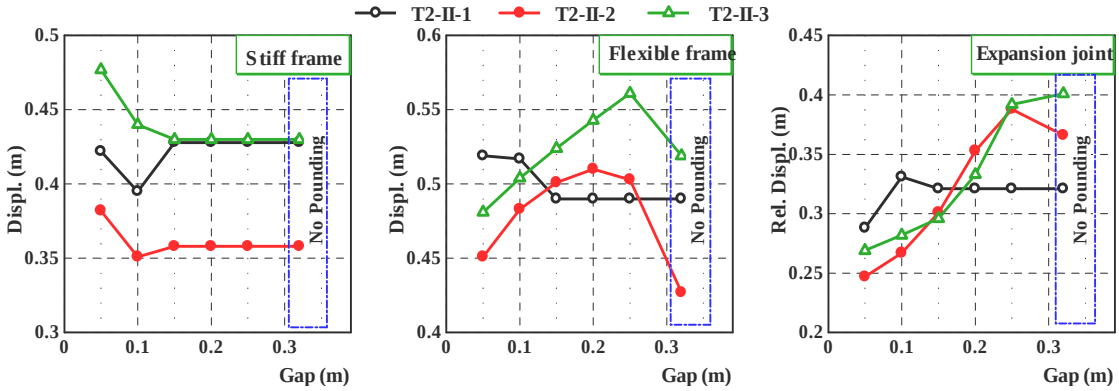

Figure 5 Variation of displacement peak response at expansion joint with gap size

4.2. Restrainers System for Mitigation of Pounding

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. However 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 as seen in **Figure 6**, the maximum pounding force in case of having restrainers is smaller than that in case of having no restrainer, but the number of pounding occurrence between adjacent vibration units is considerably increasing, but the relative displacements between the superstructure and

substructure at both left and right LRBs are slightly reduced. Hence configuration I of restrainers 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 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 at the expense of the seismic force demand of the supporting pier at the expansion joint. The main effect of restrainers upon global bridge motions is found to constrain and redistribute the relative distances between adjacent vibrations units. Therefore, it is very important to consider the pounding effect between the adjacent segments in analyzing the response characteristic of a bridge retrofitted with restrainers.

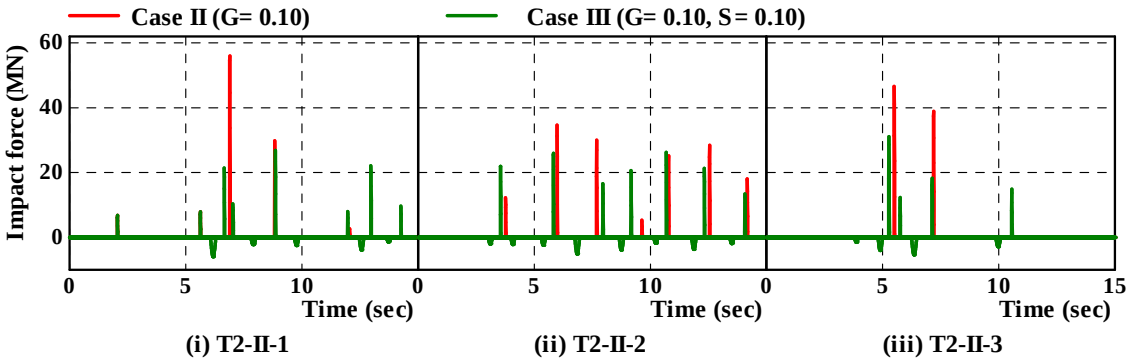

Figure 6 Impact force time history at expansion joint

4.3. Shock Absorber for Mitigation of Impact 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 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. **Figure 7** compares 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 is significantly 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 nonlinearly with joint separation with smooth stiffness change. 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.

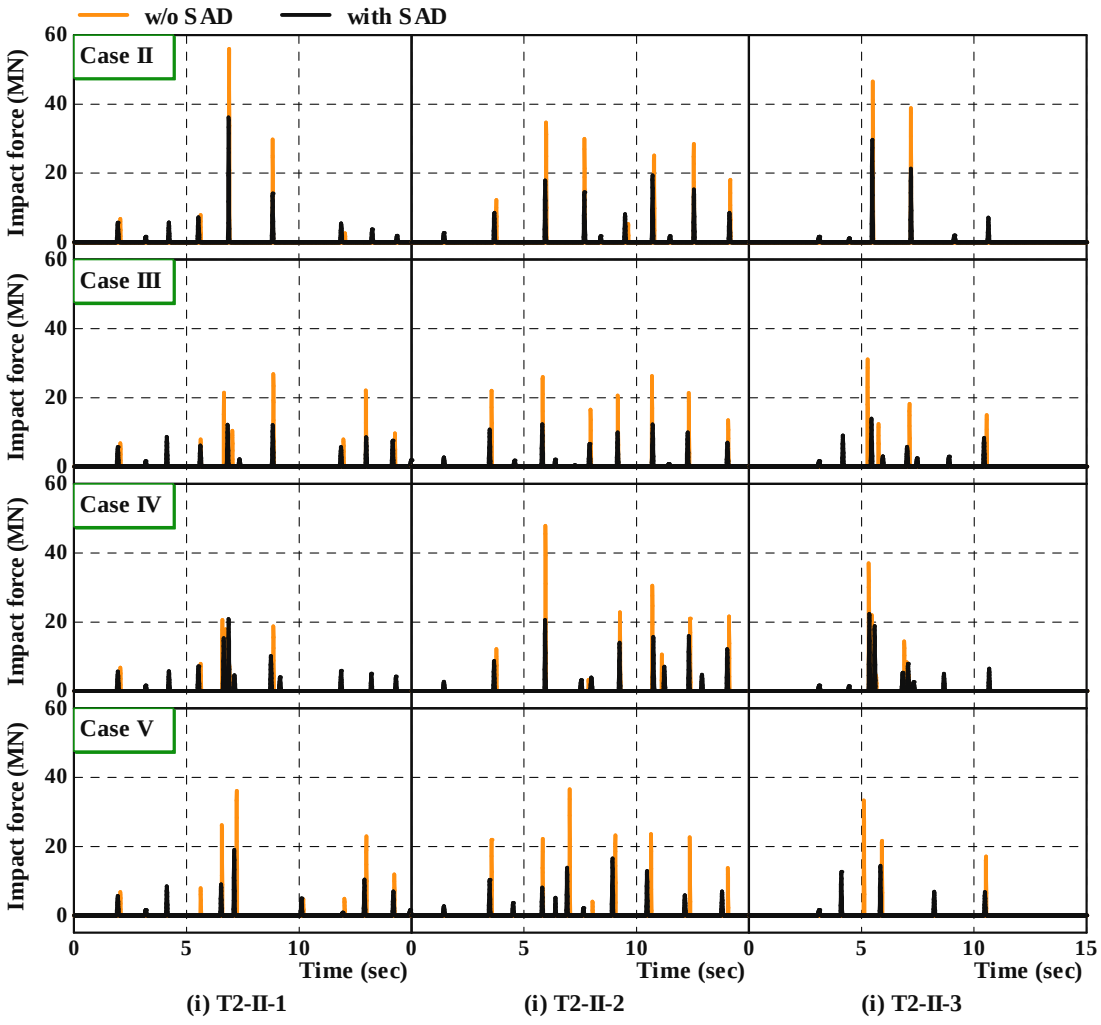

Figure 7 Impact force time history response with/without SAD

4.4. Rubber Shock Absorber Size Effects on Mitigation Efficiency

The objective of shock absorbers is to mitigate undesirable dynamic effects caused by accidental impact forces acting on the structure. The investigation of the rubber pad size effects on the impact force, relative displacement and acceleration responses at expansion joint, show that the responses are significantly decrease with the increase of rubber sock absorbing device size up to half gap/slack size, further increase of SAD size slightly enhances the responses as shown in **Figure 8**,

Hence it can be concluded that rubber shock absorbing device with size less half gap/slack size significantly provides economical and effective design that could reduce the impact force and acceleration responses. The design concept should maximize acceleration reduction, whilst minimizing the shock absorber size.

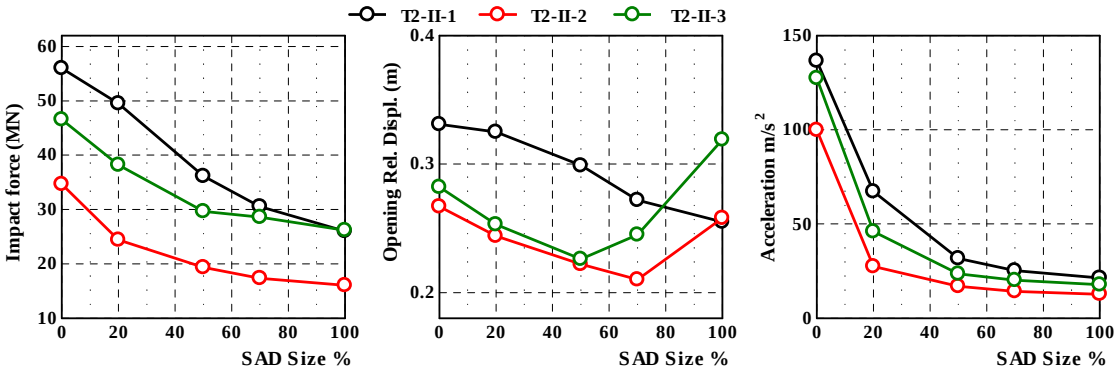

Figure 8 Peak responses variation with SAD size

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, numerical simulation by nonlinear dynamic response analysis is conducted and pounding mitigation and unseating prevention for the highway bridges seismic responses 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 pounding and unseating prevention measures due to 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 significantly higher than what is typically assumed in design 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. 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, so that in situations of potential pounding, neglecting its possible effects leads to non-conservative design.

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. 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 be carefully redesign. Restrainers were capable of reducing relative displacements through expansion joint but unseating prevention capability depends on the restrainers' configuration. 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 responses.

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