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# Effectiveness of using rubber bumper and restrainer on mitigating pounding and unseating damage of bridge structures subjected to spatially varying ground motions

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A B S T R A C T

Pounding and unseating damages to bridge decks have been observed in almost all the previous major earthquakes. Recent studies have highlighted that adjusting the fundamental periods of adjacent structural elements close to each other, the only method suggested by the codes to mitigate pounding and unseating damage, is not sufficient to prevent such damages owing to the relative displacement induced by spatially varying ground motions. As pounding and unseating damage could lead to significant loss of economy and life owing to inability to quickly access the damaged area immediately after an earthquake, it is important to protect lifeline bridge structures. Past earthquakes have revealed that the commonly used steel cable restrainers have limited effectiveness. Additionally, only limited research has focused on mitigating pounding forces on the bridge joints that lead to localized damages and disruptions of the serviceability of the bridge after strong shakings. This study presents an extensive investigation on the effectiveness of combining rubber bumpers as a shock absorbing device along with Shape Memory Alloy (SMA) or steel cable restrainers to mitigate pounding and unseating damages on multiple-span bridges subjected to spatially varying ground motions. The responses of bridge structures with different restraining devices acting alone and in combination with rubber bumpers subjected spatially varying ground motions are compared and discussed. The result indicates that the SMA restrainers combined with rubber bumpers could lead to better performance in terms of reduction of joint opening and mitigation of large pounding forces.

## 1. Introduction

Seismic pounding between girders and/or between girder and abutment in multi-span bridges has been commonly observed in almost all major earthquakes. For example, during the 1994 Northridge earthquake, significant pounding damage was observed at the expansion hinges and abutments of standing portions of the connectors at the Interstate Freeway 5 and State road 14 interchange, which was located approximately 12 km north-east of the epicentre [1]. Reconnaissance reports from the 1995 Hyogo-Ken Nanbu earthquake in Japan identified pounding as a major cause of fracture of bearing supports and potential contributor to the collapse of several bridge decks [2]. The 1999 Chi-Chi earthquake in Taiwan revealed hammering at the expansion joints in some bridges resulting in damages to shear keys, bearings and anchor bolts [3]. Failure of girder ends and bearing damage due to pounding of adjacent simply-supported spans were reported after the 2001 Bhuj earthquake in Gujarat, India [4]. Pounding damage between adjacent bridge structures were also observed in the 2008 Wenchuan earthquake [5], 2010 Chile earthquake [6] and more recently in the 2011 Christchurch earthquake [7]. The multiple-frame and multiple-span simply supported bridges are most susceptible to pounding damages due to numerous independent components and lack of continuity in the structure. It has been observed that pounding impact could induce large acceleration spikes and contact forces on the component involved, resulting in local crushing and spalling of concrete and damages to shear keys, bearing pads and restrainers and possibly contributing to collapse of deck spans. However, there are contradicting views on how pounding affects the global bridges response and the response of the piers [8]. Some studies [9] suggested pounding to be detrimental, while others [10–12] concluded pounding has a less severe effect on the response of bridge piers.

Restrainers have been in use since early 1970s as an effective device for preventing span collapse during an earthquake event

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[13]. 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 [14]. To improve the effectiveness of restrainers in bridge structure protection, many researchers have carried out research to provide appropriate design procedure for restrainers and to understand the influencing factors on the behaviour of restrainers through parametric studies. Saiidi et al. [15] have investigated four bridges retrofitted with cable restrainers during the 1989 Loma Prieta earthquake and concluded that restrainers are affected by many factors such as the amplitude and frequency of the ground motion, foundation flexibility as well as flexibility of the substructure and nonlinear time history analysis is necessary to design appropriate restrainers. Trochalakis et al. [16] conducted 216 non-linear time history analyses for various frames, abutments, and restrainer properties and showed that the maximum relative displacement were sensitive to the stiffness of adjacent frames, the frame's effective periods, and the restrainer properties. DesRoches and Fenves [17] suggested a new design procedure for steel restrainers and compared it with results of nonlinear time history analyses. DesRoches et al. [18] carried out a series of full-scale tests of a simply-supported bridge to evaluate the force–displacement behaviour of the cable restrainers. Based on these studies, it is concluded that 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 [19]. 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 analytical and experimental studies. In these studies [13,20–23] SMA based restrainers have been proposed to avoid deck unseating owing to opening relative displacement, but the pounding impact caused by closing relative displacement 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. Relative displacements between adjacent bridge structures are caused by out-of-phase vibrations owing to none identical vibration properties and inevitable ground motion spatial variations at the multiple bridge supports. However, in most of the previous studies uniform ground excitations along the bridge supports are assumed, which could significantly underestimate the responses [24–27].

Even though the destructive potential of structural pounding has been evident during almost all the previous major earthquakes, there is still not sufficient guideline provided by the seismic design codes to prevent the harmful effects of pounding between adjacent bridge structural elements. Most of the bridge design codes suggest adjusting fundamental periods of the adjacent structural elements close to each other as the only method to mitigate pounding damages in bridge structures. However, recent studies [24–26,28–31] showed that only adjusting the fundamental period of the adjacent structures is not sufficient to avoid pounding damages because of earthquake ground motion spatial variations. One of the mitigation measures for poundings of adjacent structural elements would be prevention of impact incidents by providing sufficient gaps. However, often the size of the expansion joints has to be limited for smooth traffic flow, making the adjacent structures susceptible to earthquake induced poundings. 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 [32–34] assessed the effectiveness of this impact mitigation measure on the response of bridges and buildings.

During earthquake shaking, both pounding and unseating damages are possible because of the closing and opening relative displacement between adjacent bridge structures. To mitigate the possible pounding and unseating damages, some codes [35] suggest using restrainers together with shock absorbing devices. Few researchers [32,33,36] have investigated the effectiveness of using steel restrainers and rubber bumpers together to mitigate pounding and unseating damage between adjacent decks. The incorporation of rubber shock absorbers in the expansion joints was found to be effective to mitigate large pounding forces and acceleration pulses. Although ground motion spatial variation is inevitable owing to seismic wave propagation and non-uniform ground motion generates relative responses between adjacent structures, owing to the complexity in modelling such variations, all the above reviewed studies assumed uniform ground motion in the analysis. Moreover, no study that investigates the effectiveness of using SMA restrainers with rubber bumpers in mitigating pounding and unseating damage of bridge structures has been reported in the literature yet.

There is a clear consensus among the researchers that pounding results in localized damages at impact locations and could contribute towards unseating of the bridge spans. This paper investigates the effectiveness of combining rubber bumper with either SMA restrainers or steel restrainers on multiple-frame bridges with one or more intermediate gaps to mitigate these damages subjected to spatially varying ground motions. The study focuses on the balanced frames which are emphasized by the prevailing codes as a method to mitigate relative displacement induced damages such as pounding and unseating. The study firstly compares the effectiveness of the steel and SMA restrainers to mitigate the large joint opening. Then the effectiveness of rubber bumpers as a possible pounding mitigation device is investigated. Parametric studies are carried out to compare the effectiveness of the two types of restrainers along with rubber shock absorbing pads to mitigate pounding and unseating damage on bridges subjected to spatially varying ground motions corresponding to different site conditions. Based on the numerical results, conclusions on the effectiveness of using the rubber bumpers with restraining devices to mitigate pounding and unseating damage are drawn. This study sheds some light on the benefits and limitation of the aforementioned restraining devices and shock absorbers when acting alone or in combination. The results presented could assist bridge engineers on selecting the devices to effectively mitigate relative displacement induced damages on bridge structures.

## 2. Numerical model

### 2.1. Bridge model

Without loss of generality, two typical Californian Highway Bridges with five spans are selected for the analysis. The expansion joints 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 either reinforced or pre-stressed concrete. The bridge details are described in Feng et al. [37] and Kim et al. [38]. For readers' easy reference, the bridge parameters are also presented here in Table 1. Two 2-D nonlinear finite element models of the bridges shown in Fig. 1(a) and (b) are developed for the analysis, which represent

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

The bridge models are developed in the nonlinear software package Seismostruct [39]. Previous studies [35,36] used a bilinear