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# Numerical Investigation on Rotational Friction hinge damper based restrainers to mitigate relative displacement induced damages in simply supported bridges

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## Abstract

Restraining devices are the most commonly used retrofit method to inhibit the relative movement at bridge joints that could cause unseating of the spans. The present research stems from the fact that the existing restraining devices which are based on cables are not able to mitigate pounding impact between the adjacent structures and could result in the build-up of large forces that could lead to either failure of the restrainers and/or connecting element or transfer large forces to the adjacent frame/span/abutment. Previous studies have highlighted that the damping could be more effective than the stiffness on mitigating the relative displacement-induced damages in bridge structures. This study proposes the use of Rotational Friction Hinge Damper (RFHD) based restrainers to mitigate damages induced due to relative displacement and pounding between adjacent structures at bridge joints. The paper presents results of a numerical investigation on the effectiveness of these devices on a typical Nepalese simply supported bridge subjected to spatially varying ground motions. The results presented indicate that RFHD devices are very effective in mitigating relative displacement as well as the pounding forces.

**Keywords:** Relative displacement, pounding, restrainers, Rotational Friction Hinge Dampers, spatially varying ground motions

## 1. INTRODUCTION

Damages to bridge structures can be catastrophic in the event of a strong earthquake. Closure of the damaged bridges, particularly critical lifeline structures, will block emergency services to those in a heavily damaged area immediately after an earthquake. Recently, in order to improve the seismic resistance of bridges, elastomeric bearings have been widely used. Seismic isolation is an innovative seismic resistant design approach that decouples the bridge superstructure from the substructure, reducing the transmitted forces to the piers and abutments. However, incorporation of seismic isolators introduces flexibility at the isolation level due to which the displacement of the bridge deck increases. This increase in displacement enhances the possibility of pounding between adjacent decks or between a deck and an abutment as the usually provided gap size is not sufficient to avoid seismic pounding. Pounding of adjacent bridge structures can not only result in damage at the expansion joints and contact faces but can also extend the damage to adjoining bearings and piers. It can also amplify relative displacements and contribute towards unseating of bridge spans (Otsuka et al. 1996). The earthquake design codes, such as Japanese Road Association (2004) specify that the gap size between bridge segments should be large enough to avoid pounding. However, the size of the expansion has to be limited to allow traffic to flow smoothly over the bridge.

It is desirable to mitigate the pounding and unseating damages on bridges. In fact, cable restrainers have been in use now for a few decades to mitigate the unseating damages and are the most widely adopted retrofitting method. However, restrainers are only effective to mitigate unseating damages caused by opening relative displacement and cannot mitigate pounding impacts caused by closing relative displacement. Even though both pounding and unseating damages are possible during seismic events, only a few studies have focused on retrofitting devices that can mitigate both of these damage types. Moreover, commonly used steel and SMA restrainers basically rely upon their stiffness to limit opening relative displacements. This can result in either failure of the restrainers or the connecting element or transfer of large forces to adjacent frame/deck/abutment significantly altering a bridge’s seismic response. Few researchers (Abdel Raheem 2009; Zhu et al. 2004; Kawashima and Shoji 2000; Shrestha et al. 2014) have investigated the use of rubber bumpers and restrainers to mitigate damages induced by both closing and opening relative displacements. Feng et al. (2000) and Kim et al. (2000) investigated the use of energy dissipating restrainers to mitigate the damages at expansion joints. The latter studies reported that energy dissipating devices could be a practical solution to the seismic problem arising on bridges with expansion joints. Additionally, it was found that supplemental damping could be significantly more effective than the stiffness on reducing the relative displacement at bridge expansion joints.

Even though, there exists spatial variability of the ground motions along the length of the bridge that is inevitable due to the wave travelling and different soil conditions, most of the previous studies have neglected this fact. Previous studies have either used uniform motions or considered only the wave passage effects (for example. Jankowski 2000), while studying the effectiveness of retrofit devices. To the best knowledge of the authors, apart from the study of Shrestha et al. (2014a, 2014b), none of the previous studies have modelled the ground motion’s spatially variability in detail to evaluate the effectiveness of pounding and unseating mitigation devices. It is to be noted that relative displacement on bridge structures have proven to be significantly affected by spatially varying ground motions (Chouw and Hao 2008). Hence, the study on the use of retrofit devices to mitigate the relative displacement induced damages without considering the spatial variability of ground motions along the length of bridge may provide unrealistic results.

In this study, the effectiveness of Rotational Friction Hinge Dampers (RFHD) based restrainers on mitigating the relative displacement induced damages at the bridge joints is investigated. These devices have large hysteretic energy dissipation potential at a reasonable cost and are easy to install and maintain. Recently, several friction devices have been tested experimentally and some of these have been implemented in buildings around the world (Mualla et al. 2002; Nielsen et al. 2004). However, the efficacy of these friction devices in mitigating the relative displacement induced damages in bridge structures has not been explored. In this study, spatially varying ground motions are applied to get realistic estimates of relative displacement at bridge joints and to evaluate the efficacy of retrofit devices to mitigate the relative displacement induced damages. The analysis is conducted on a typical Nepalese simply supported bridge with four spans of 25 meters each.

## 2. ROTATIONAL FRICTION HINGE DAMPERS

The Rotational friction hinge device (V-type) consists of two rigid plates connected in the rotational hinge, and the plates are separated by several shims of friction pads as seen in Figure 1(a). The moment-rotation behaviour in the hinge is elastic-frictional. The dampers are used in bridge structures with the two plate end points connected to the pier and deck of the bridge, respectively, as shown in Figure 1(b). The presented connection scheme is used to control the only longitudinal motion of the bridge; however, the connection scheme can be modified to control both longitudinal and transverse bridge vibration. During a seismic event the distance between connection point changes, due the induced seismic motion and the angle between the damper plates also changes in the hinge. Upon reaching the frictional resistance of the device in torsion, slip and relative rotation between the damper plates take place, thus dissipating a portion of the kinetic energy of the structure. The sticking and sliding modes of the RFHDs succeed each other until the end of motion (Nielsen et al. 2004).

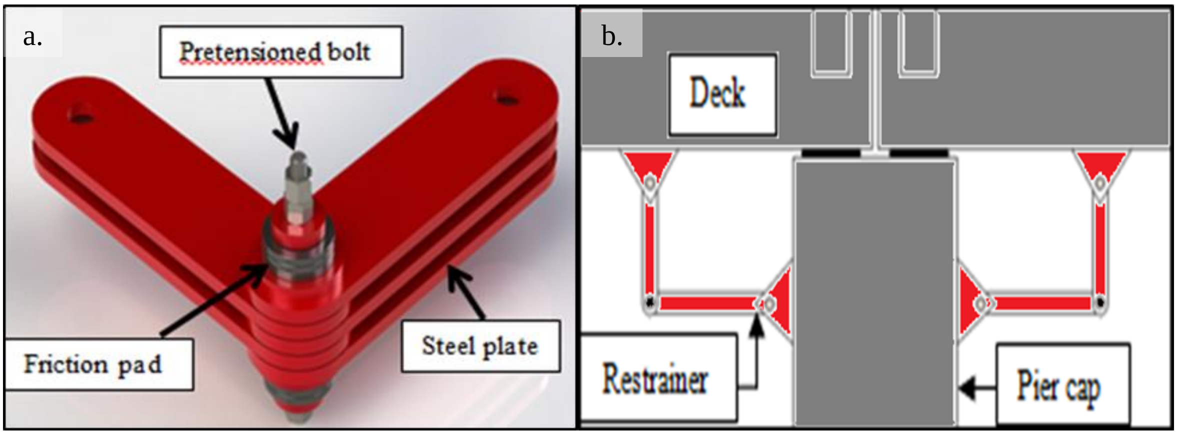

**Figure 1.** Rotational friction hinge damper; (a) Overview, (b) Connection Scheme

As shown above, the damper has a very simple mechanism that makes it easy to assemble and install. The simplicity allows for constructing devices with multiple units in order to match the required design frictional resistance and space limitations. When applied, the dampers should be placed parallel to the longitudinal axis of the bridge. In addition, a hydraulic lock-up device that can absorb slow movements such as thermal expansion but transmit the shocks from high frequency movement such as earthquake could be placed along with the device.

## 3. NUMERICAL MODEL

The bridge model, as presented in Figure 2, is a typical simply supported bridge in Nepal. The bridge has four spans of 25m each. The piers are 1.6m in diameter, reinforced with 55Ø32 steel bars with total pier height (including pier cap) of 6m. The bridge deck is slab on girder type construction with three girders of 2 meter depth. The abutment is a seating type with back wall 2m high and width and length of 0.94m and 7.2m, respectively. The pier foundations are assumed to be supported on well foundation of diameter 6 m and depth 13 m. Laminated rubber bearings of 50 mm thickness are fitted at the outer ends of each span. Expansion joints with a gap width of 25mm are located between deck-deck (Gap2, Gap3& Gap4) as well as abutment-deck connections (Gap1 & Gap5). The details of the bridge components are presented in Figure 3. As shown, the piers and abutments are provided with shear keys that inhibit the lateral movement of bridge decks. Thus in this study only the longitudinal vibration of the bridge, which could result in pounding and unseating, is considered.

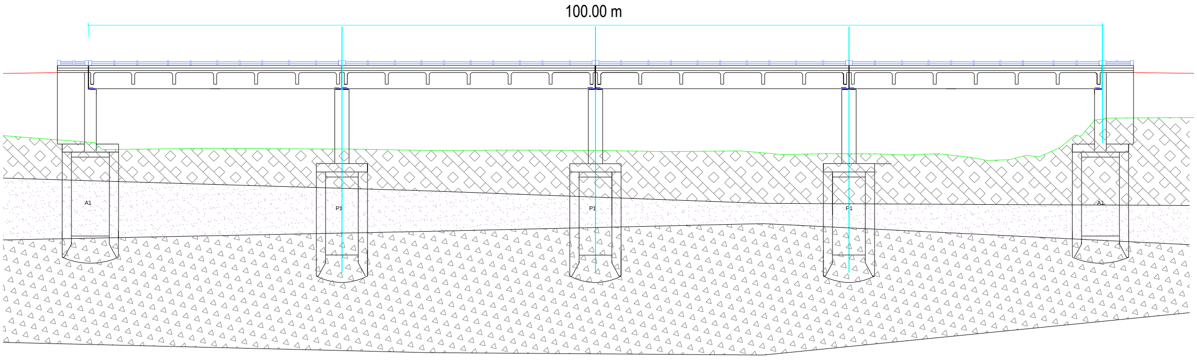

**Figure 2.** Longitudinal section of the bridge

This study has been carried out in the nonlinear seismic response analysis program SeismoStruct. In what follows, results from the dynamic time-history analyses are presented to evaluate the inelastic response of the bridge subjected to earthquake loading, as well as the performance of RFHD. In this study a 2-D model of the bridge is developed and lumped stiffness and lumped yield/slip forces are used for modelling the bearings and dampers. The mechanical model of the bridge is presented in Figure 4. RLink refers to rigid links that connect the top of the piers to the center of gravity of the bridge deck, AbutSpr are abutment springs, Br2L refers to the bearing at Pier 2 that supports the deck at the right side, VtypeiL refers to RFHD at $i_{th}$ pier and ultimate sentence L refers to left side of the pier where it is fixed. The foundation of the bridge piers is assumed to be fixed in this study. The laminated rubber bearings are modelled using a bilinear kinematic curve. A single spring is used to represent the three bearings placed beneath the deck girders. The post-yield stiffness to pre-yield stiffness ratio is taken as 0.1 to provide the maximum energy dissipation. The initial stiffness and yielding force are calculated as 13248 kN/m and 98.5 kN, respectively. Bilinear elasto-plastic curves were used to model the RFHD. The hysteretic behaviour of the RFHD is presented in Fig 5(a). Stiffness of RFHD in the stick phase is taken as 18000 kN/m based on a previous study by Chen and Hao (2013). A linear impact spring with stiffness proportional to the axial stiffness of the adjacent bridge deck is used to represent the impact between adjacent decks and deck to abutment.

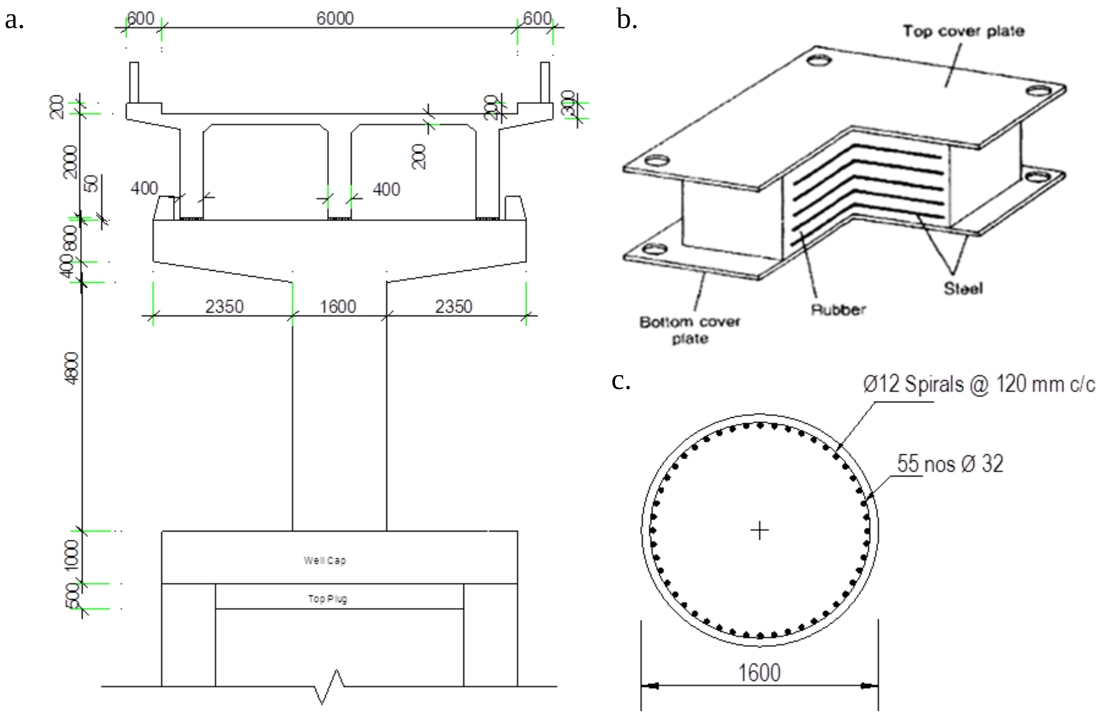

**Figure 3.** Bridge component details; (a) bridge section, (b) bearing detail, (c) Pier section (all dimension in mm)

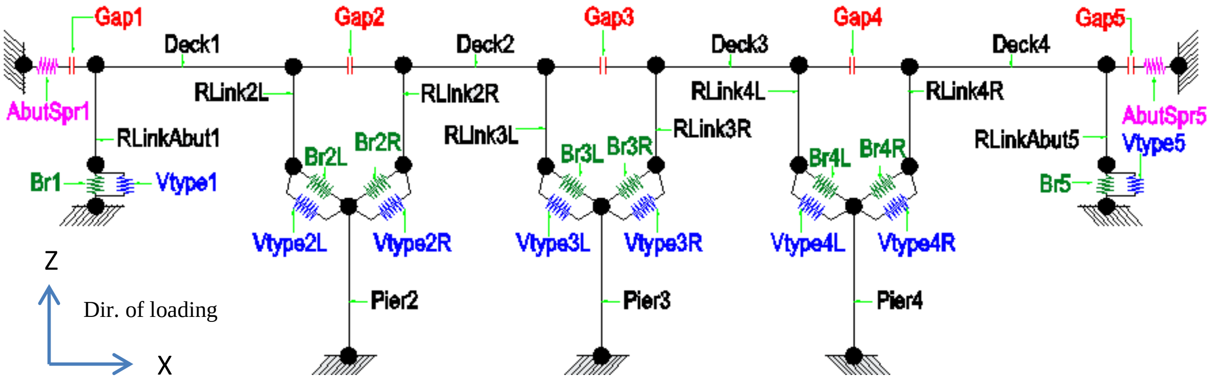

**Figure 4.** Mechanical model of the bridge

## 4. GROUND MOTIONS

The method proposed by Bi & Hao (2012) is used to simulate spatially varying ground motion time histories. In this study, the amplified Indian code Type III spectrum (IS 1893, 2002) with peak ground acceleration of 0.65 g is used. The PGA value adopted in this study was determined in recent Probabilistic Seismic Hazards Analysis (PSHA) (Parajuli 2009, Ram and Wang 2013) for regions in Nepal for less frequent earthquake events that should be used for designing lifeline bridge structures. The spatial variation properties between ground motions recorded at two locations j and k on the ground surface is modelled by a theoretical coherency loss function (Sobczky 1991)

$$\gamma_{jk}(i\omega) = \left|\gamma_{jk}(i\omega)\right| \exp(-i\omega d_{jk}\cos\alpha / v_{app}) = \exp(-\beta\omega d_{jk}^2 / v_{app}) \cdot \exp(-i\omega d_{jk}\cos\alpha / v_{app}) \qquad (5)$$

In this study, $\beta = 0.001$, whereas $v_{app}$ and $\alpha$ are assumed to be 500 m/s and 45°, respectively. To obtain a relatively unbiased response, 5 sets of ground motion time histories (GM1 to GM5) are simulated. Sampling frequency is set to fs = 100 Hz, and duration of 20.47s is selected.

## 5. RESULTS AND DISCUSSIONS

### 5.1 Effectiveness of RFHD

To evaluate the effectiveness of the RFHD when subjected to spatially varying ground motions, models with and without the V-type damper were analyzed and compared. In this section, without losing the generality, only the case with the damper slip force of 186kN is presented. Figure 6 shows the mean of the peak pounding forces of five ground motions for five bridge gaps. As shown, the dampers are capable of reducing the closing/opening displacement and peak pounding forces. Figure 7 presents the opening relative displacement at the bridge joints. Clearly the RFHD has significant impact on the relative displacements as well, except at the Gap 4, however, the opening displacement at the joint is small. As shown, the device is very effective when the relative displacements are large, because the efficacy of the device depends upon the opening of the joints. The greater the opening of the joints the more effective the device would be in dissipating the energy.

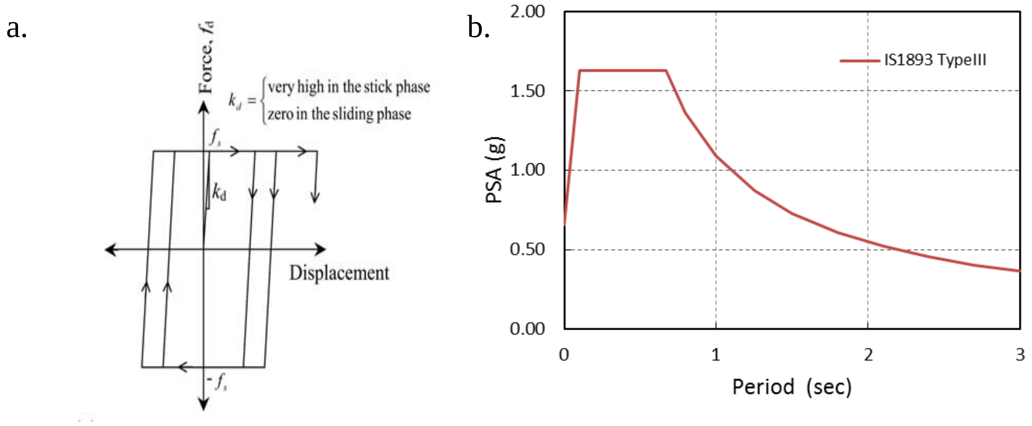

**Figure 5.** (a) Idealized hysteretic behaviour of RFHD ; (b) Comparison of 1000 years return period spectrum for Kathmandu valley and design spectrum

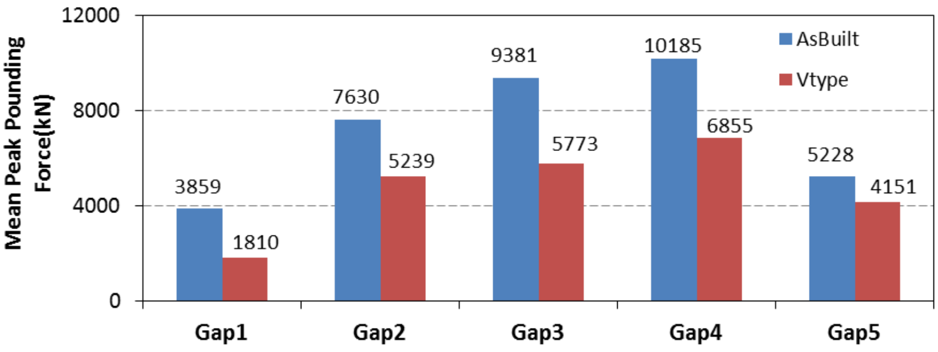

**Figure 6.** Comparison of mean peak pounding forces at the bridge joints

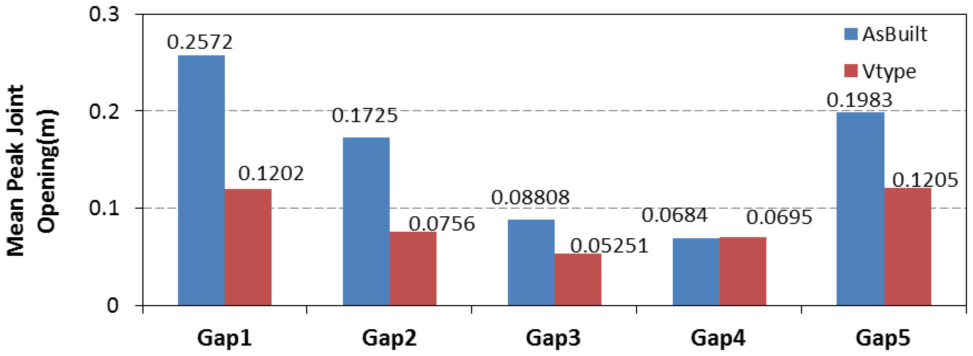

**Figure 7.** Comparison of mean peak joint opening at the bridge joints

## 5.2 Effects of Slip force of RFHD

In order to identify the effects of slip forces of RFHD, parametric analysis on the devices with various slip forces was conducted. In this study, five damper slip forces 93,186,280,373 and 466 kN were investigated to identify the effect of damper slip force on the bridge's response. Figure 8 presents a comparison of the hysteretic response of the damper with slip force of 93 kN and 466 kN. It is observed that the increase in the slip force usually results in reduction of damper deformation and in some cases may form an incomplete loop, suggesting a reduction in energy dissipation as well as the presence of some residual displacements. Figure 9 compares the mean peak pounding forces at five joints of the bridge for 5 sets of ground motions. The pounding forces are significantly reduced due to the application of RFHD. In general, the RFHD with highest slip forces resulted in largest reduction in the peak pounding force. However, the results presented also suggest that RFHDs with lower slip forces are also effective in mitigating the pounding force as these devices are capable of dissipating energy similar to that of a RFHD with higher slip forces. Figure 10 shows the peak opening joint displacement at 5 bridge joints. The results show that the RFHDs are extremely effective when the relative displacements at the joint are large. The effectiveness of the devices at joint 3 and 4 are small, however, the relative displacements are also small. Figure 11 compares the hysteretic behaviour of the piers with RFHD slip forces of 93 kN and 466 kN, respectively. Due to the larger slip force, significant forces are transferred into the substructure for the device with higher slip forces. However, the pier's response is essentially elastic.

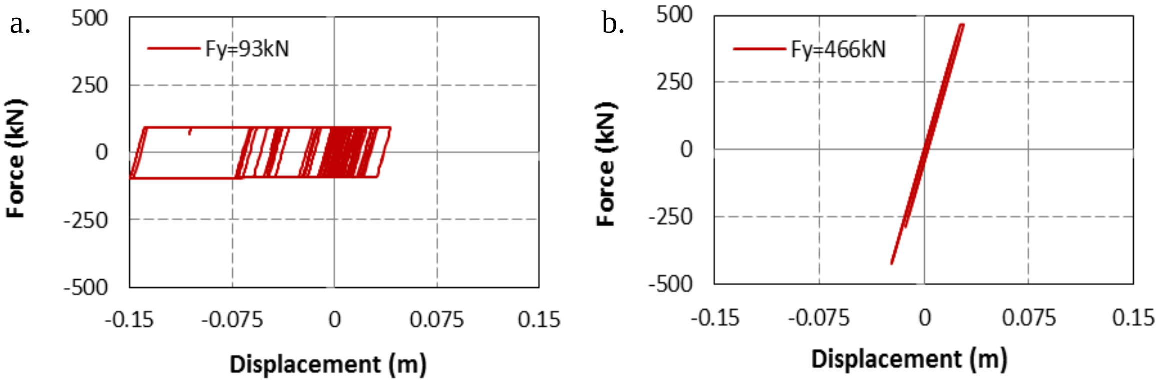

**Figure 8.** Comparisons of damper performance (a) yield force 93 kN; (b) yield force 466 kN

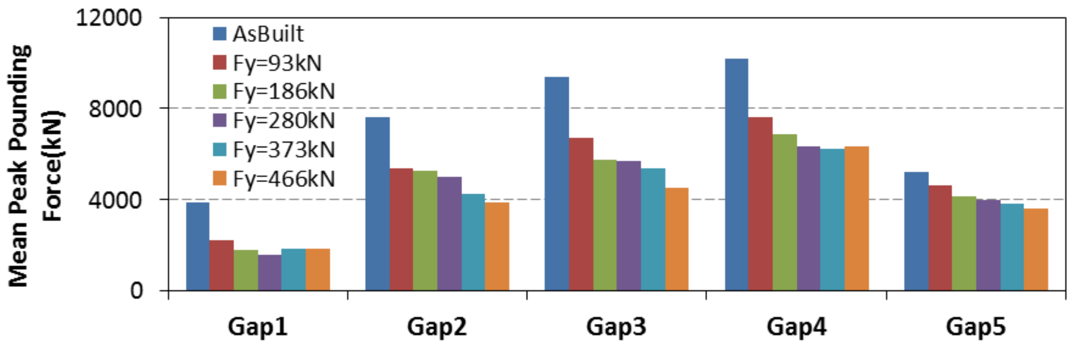

**Figure 9.** Comparisons of mean peak pounding force at the joints

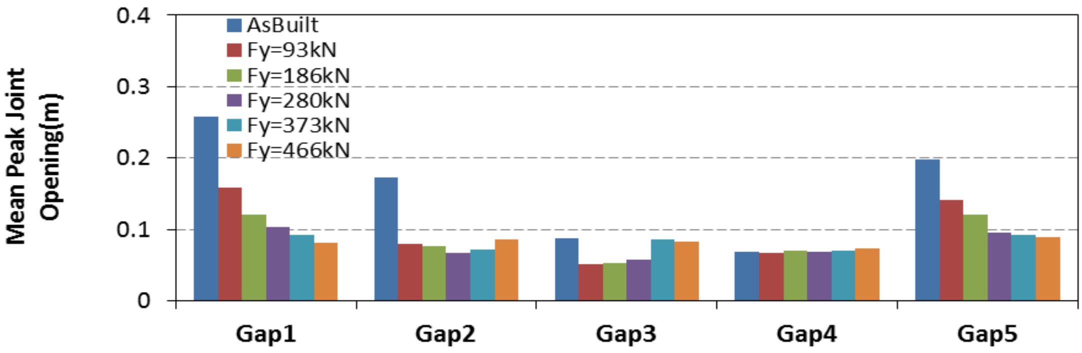

**Figure 10.** Comparisons of mean peak joint opening

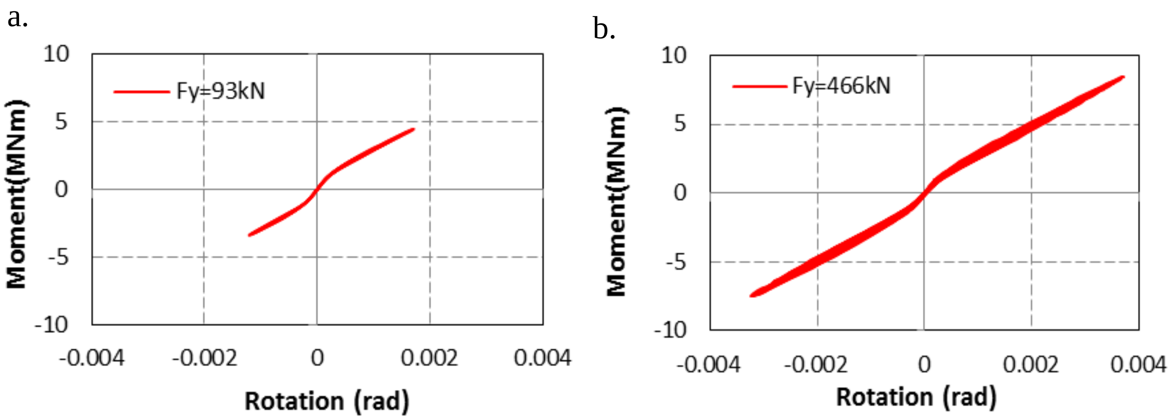

**Figure 11.** Comparisons of pier response with RFHD slip force (a) 93kN; (b) 466 kN

## 6. CONCLUSION

This paper proposes using RFHD devices to mitigate relative displacement induced damages in simply supported bridges. Five sets of spatially varying ground motion along the supports of the bridges are used to simulate realistic relative displacement responses of the bridges. The bridge model and the simulated ground motions are based on typical Nepalese bridge and seismic hazard of Kathmandu region, respectively. The numerical analyses conducted in this study suggest that RHFD could be a good retrofit option to mitigate the pounding and unseating damages in bridges. The device is capable of significantly reducing the responses at bridge joints by dissipating the energies. Higher slip force for a device may not result in larger energy dissipation or higher reduction of responses at joints, however, could increase the response of the piers. The results presented in the paper suggest that the device is suitable retrofit option regardless of its slip force. The effectiveness of the device is not significantly affected by the slip forces thus small variations of the slip forces during the life time of the bridge would not warrant any adjustment or the replacement of the device.

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