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Evaluation of Seismic Risk Mitigation Techniques for RC Bridge Superstructure Vulnerable to Pounding

Jumana Hasina[1], Aman Mwafy[1], Anas Issa
[1]Dept. of Civil and Environmental Engineering, United Arab Emirates University
Al Ain, UAE
700039093@uaeu.ac.ae; amanmwafy@uaeu.ac.ae; anasalemissa@gmail.com

Abstract - Observations from previous earthquakes worldwide have shown that existing bridges designed using outdated seismic standards are vulnerable to various damage modes, such as pounding and bearing displacement, highlighting the necessity of retrofitting. This study evaluates the effectiveness of different retrofit measures to upgrade the reinforced concrete bridge superstructure, namely steel dampers and rubber bumpers, aiming to reduce seismic demands and control movement. The numerical modeling approach of the selected retrofit systems is verified by comparing the hysteretic behavior with previous experimental results. The validated retrofit strategies are subsequently implemented on the three-dimensional model of a multi-span adjacent reference bridge commonly found in a medium seismicity region. Preliminary assessments performed on the existing and un-retrofitted bridge models indicated that the bridge superstructure's fundamental natural period of vibration is shortened due to the adopted retrofit measures. Fragility relationships are derived under various seismic scenarios to evaluate the seismic performance of the retrofit techniques through incremental dynamic analyses. The probabilistic assessment results indicate that the steel dampers effectively reduce bearing displacement demands, and rubber bumpers adequately decrease pounding force between adjacent bridges. This study thus helps select effective retrofit systems for upgrading the seismic performance of bridges vulnerable to different damage modes and mitigating their seismic risk.

Keywords**:** RC adjacent bridges, Probabilistic assessment, Structural failure, dampers, Rubber bumpers.

1. Introduction

Seismic performance improvement of existing reinforced concrete (RC) bridges can be achieved by decreasing seismic demands and controlling movement between adjacent structural components [1]. Reducing a structure's dead load decreases inertia forces and consequently lowers seismic demand. This can be achieved by replacing RC bridge decks or heavy barriers with lightweight materials [2]. Moreover, Previous research on non-seismic rubber isolators integrated with shape memory alloy (SMA) dampers demonstrated improved energy dissipation and reduced residual deformations. However, in high-damping isolators, the effect of SMA dampers on reducing residual deformations was minimal [3]. Therefore, yielding steel dampers were proposed to control bearing displacement and reduce the risk of superstructure unseating caused by bearing sliding [4]. However, most prior studies have focused on experimental investigations of bearing components. Additional seismic performance assessment studies are still needed for existing RC bridges retrofitted with contemporary steel dampers.

Moreover, seismic pounding between bridge deck segments or between the deck and abutments in multi-span bridges has been frequently observed during strong earthquakes due to a limited separation gap between the bridge components. Therefore, conventional steel restrainers were employed to mitigate collisions between adjacent structural segments, but their effectiveness is limited by a small elastic strain range and low ductility capacity [5]. Experimental studies have shown that using rubber as a shock-absorbing material effectively reduces structural collisions due to its high-damping properties [6]. Similarly, numerical studies have demonstrated the advantages of rubber bumpers placed between structures with narrow separation gaps in mitigating the pounding effects by reducing peak acceleration and limiting excessive horizontal displacement [7]. However, most prior research has primarily concentrated on developing models for pounding mitigation and conducting experimental tests at the component level. This study thus aims to investigate the effect of contemporary steel dampers and rubber bumpers in mitigating seismic demand and reducing collisions in adjacent bridges.

2. General Description and Fiber-based Modeling of the Reference Bridge

The selected reference structure is a multi-span adjacent RC bridge in a medium seismicity zone represented by the United Arab Emirates (UAE). Given its construction period, the bridge was categorized as, emphasizing its possible susceptibility to various damage modes, such as pounding, under different seismic conditions. Previous studies classified the UAE as a region with low-to-moderate seismicity, vulnerable to both near-field (NF) and far-field (FF) earthquake ground motions [8, 9]. The reference bridge comprises two identical structures placed adjacent to each other, separated by a narrow separation gap of 20 mm, as illustrated in Fig. 1. The superstructure is a five-span RC deck supported on RC girders, and it rests on the substructure through elastomeric bearings. The substructure consists of four sets of bents spaced 14 meters apart in the longitudinal direction.

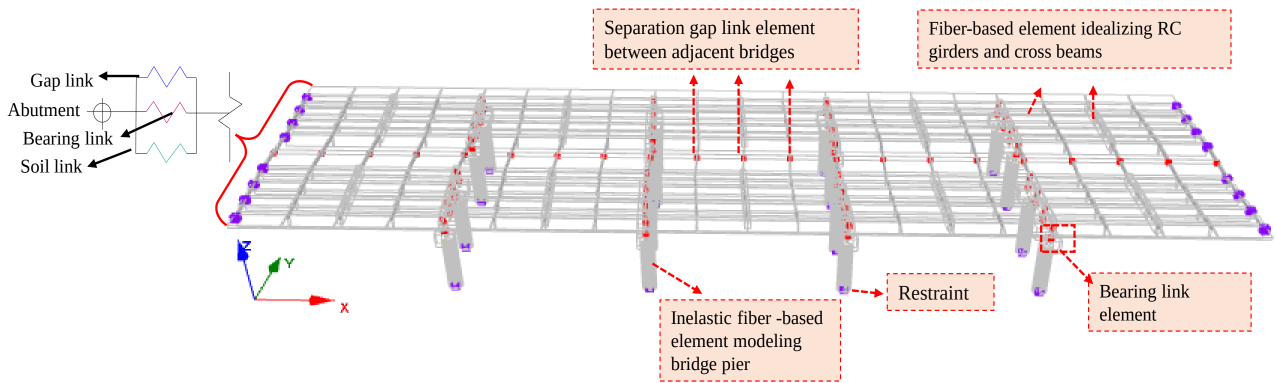

Fig. 1: Fiber-based model of reference bridges vulnerable to pounding.

An experimentally verified fiber-based analysis platform is used to develop a detailed three-dimensional (3D) model of the reference bridge structure, as illustrated in Fig. 1 [10-12]. The bridge's superstructure and substructure components are modeled with a uniaxial nonlinear concrete model [13]. The reinforcing steel behavior is represented using the uniaxial stress-strain model [14]. The RC girders of the superstructure and the substructural elements, including the columns and cap beam, are idealized using an inelastic displacement-based (DB) frame element to capture the reference structure's seismic response precisely [10]. The 20 mm separation gap between the identical bridges is modeled using a trilinear asymmetric link element, which captures collision and slippage at the expansion joints [15]. According to the modeling approach for the expansion joints, a positive relative displacement indicates an opening of the joint gap, while a negative displacement represents a gap closure [10, 16]. The bearing model is also represented using a trilinear asymmetric link element, reflecting the bearings' properties necessary for calculating their stiffness in longitudinal and transverse directions [16].

3. Numerical Modeling and Implementation of Chosen Retrofit Techniques

To enhance seismic performance and control relative displacements between the pier and girder through hysteretic energy dissipation, X-shaped steel dampers are employed alongside the existing bearings of the reference bridge. These steel dampers are selected as a retrofit solution due to their effective energy dissipation properties and functionality as fuses, which can be easily installed and replaced after an earthquake. The modeling approach for the steel damper is validated through previous quasi-static experiments on X-shaped steel dampers, with each plate having a thickness of 10mm [4]. In the current simulations, the mechanical behavior of the steel damper is modeled using a link element and the Ramberg-Osgood stress-strain model, defined by model-calibrating parameters such as yield strength and yield displacement [10, 17]. Fig. 2(a) shows that the hysteretic response from the current simulation correlates well with the previous experimental results, validating the dampers' usage in the reference bridge for the retrofit measure. In the reference bridge's numerical modeling, the steel damper's connection with the cap beam and bridge girder is idealized with the help of rigid arms.

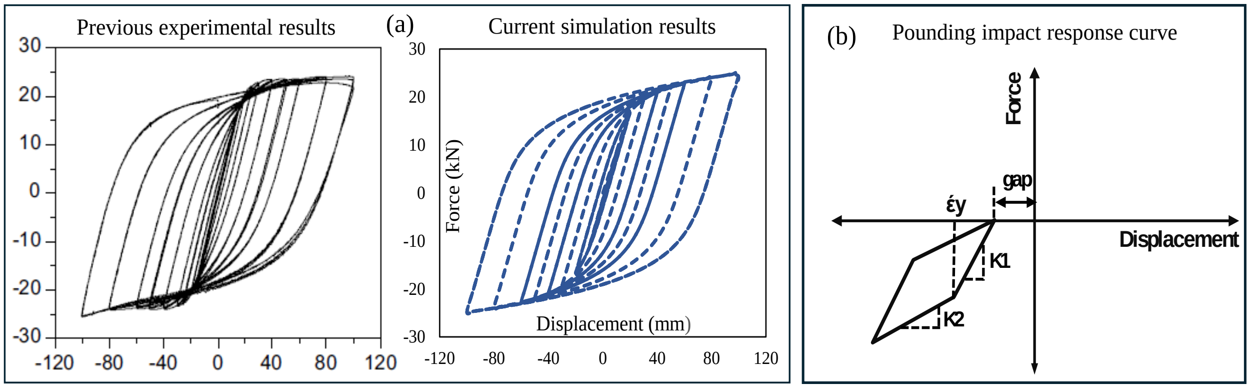

Fig. 2: Modeling approach of the steel damper and rubber bumper: (a) Previous experimental test results (left) [4] and current study simulation results (right) of steel damper, and (b) modeling of the rubber bumper.

Since the selected reference bridge is susceptible to pounding between adjacent structures, which can amplify relative displacements, leading to span unseating, this study proposes rubber bumpers as a shock-absorbing device to reduce pounding forces and control movement between adjacent bridges. The rubber bumper is idealized as a contact element that monitors the gap between the adjacent bridges and becomes active when the associated gap is closed. Twenty-one rubber bumpers, each measuring 250 mm by 150 mm in size and 20 mm in thickness, are placed between the separation gaps of the reference adjacent bridges, as shown in Fig. 1. The bumper thickness is selected considering that increasing the bumper thickness beyond 50% of the gap width would reduce the peak pounding force and relative joint opening displacement [18]. The pounding link element is idealized using an impact response element following Hertz law, as illustrated in Fig. 2(b) [19]. It is worth noting that both the retrofit measures are economical and easy to install without disrupting the regular flow of traffic and ensure continuous bridge functionality. The bridge retrofitted with the chosen mitigation measures is assessed for seismic performance improvement through preliminary analysis, followed by a detailed analysis procedure, which will be discussed in the upcoming sections.

4. Preliminary Assessment of the Existing and Retrofitted Structures

Eigenvalue analysis is conducted on the fiber-based model of the reference bridge and its retrofitted variants, serving as an initial validation method for the analytical models. This elastic analysis evaluates the structure's natural frequencies and their mode shapes. The first mode of vibration observed in the transverse direction of the existing bridge's superstructure is 0.688, as shown in Table 1. After retrofitting with the adopted retrofit measures, the first natural period of the superstructure is shortened by 26% compared to the existing bridge's period, reflecting the seismic improvements achieved in the whole bridge. The eigenvalue analysis results demonstrate the advantages of utilizing this simple analysis method as an initial assessment tool to evaluate the effects of the adopted retrofit alternatives on the reference structure's dynamic properties.

Table 1: Superstructure natural periods for the existing and retrofitted bridges in the transverse direction.

Assessed bridge	**Period (s)**
Existing adjacent bridges	0.688
Bridges retrofitted with steel damper and rubber bumper	0.543

5. Detailed Assessment using Fragility Analysis

The dynamic seismic response of the reference bridge and its retrofitted variants is evaluated through incremental dynamic analysis by subjecting the bridge to seven FF and seven NF earthquake records [20, 21]. The FF seismic records are scaled to intensity levels ranging from half the design intensity (0.5D) to 3.5 times the design intensity (0.08g to 0.56g), with increments of 0.5D. The NF ground motions are scaled from the design intensity to thirteen times the design intensity (i.e., 0.16g to 2.08g), with an increment of 2D. The scaled seismic records are applied in the transverse direction of the bridge, and the corresponding fragility curves are obtained [22]. Four levels of damage states, namely slight (SL), moderate (MO), extensive (EX), and complete (CO), are defined to evaluate the likelihood of exceeding bearing displacement (BD) and pounding force (PF) demands for both the retrofitted and un-retrofitted bridge. The probabilistic seismic performance evaluation demonstrates a higher vulnerability of the reference bridge to BD and PF under both seismic scenarios. Figs. 3(a) and 4(a) illustrate that the reference bridge exhibits slightly higher probabilities of exceeding different limit states for BD under FF seismic scenarios than the NF earthquake records. Moreover, the steel dampers significantly reduce BD across all four damage states under both seismic scenarios, with the pronounced effectiveness observed under FF records as depicted in Fig. 3(b). This reduction in BD is due to the dampers' stable hysteretic behavior and effective energy dissipation capacity, which helps lower the bearing deformation demands.

As shown in Figs. 3(a) and 4(a), the un-retrofitted reference bridge is more vulnerable to PF for different limit states under the FF and NF seismic scenarios. The rubber bumper retrofit strategy substantially improves PF for the SL limit state, with significant reductions observed for the MO and EX limit states. Notably, the CO limit state is eliminated under both long and short-period seismic scenarios, highlighting the exceptional effectiveness of the retrofit strategy in minimizing pounding forces between the adjacent bridges as illustrated in Figs. 3(c) and 4(c). Therefore, the probabilistic seismic performance assessment confirmed that steel dampers effectively reduce BD seismic demands, whereas rubber bumpers significantly control movement between the adjacent reference bridges.

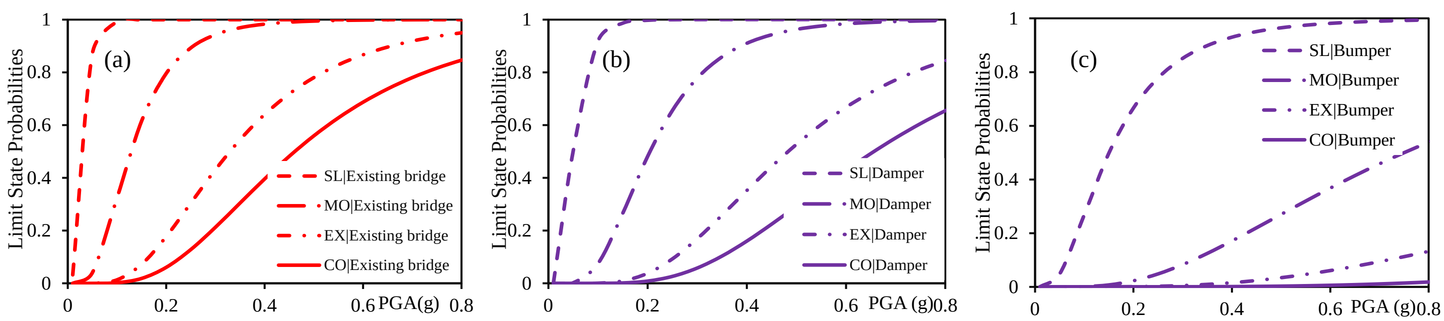

Fig. 3: Effect of retrofit measures under long-period seismic scenario: (a) un-retrofitted bridge, (b) steel damper's effect in reducing bearing displacement (BD), and (c) rubber bumper's effect in reducing pounding force (PF) demands.

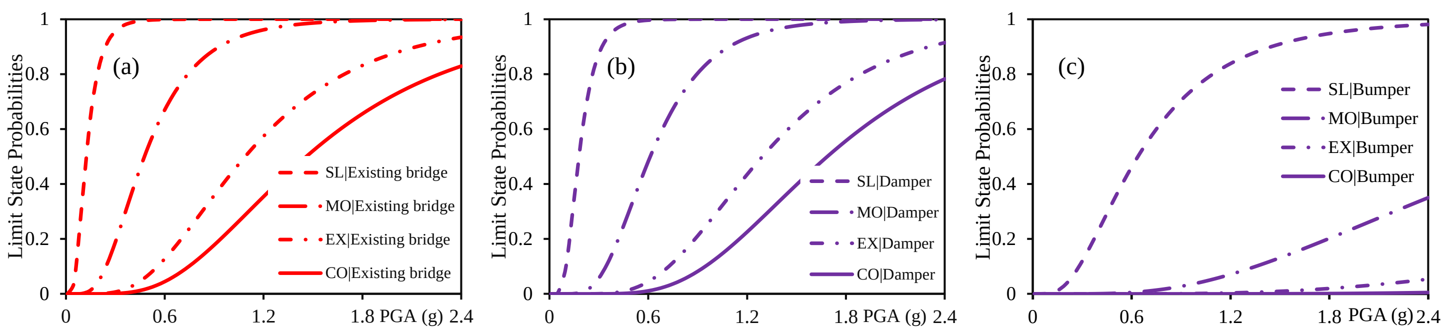

Fig. 4: Effect of retrofit measures under near-source seismic scenario: (a) un-retrofitted bridge, (b) steel damper's effect in reducing BD, and (c) rubber bumper's effect in reducing PF demands.

6. Conclusion

This study focussed on the probabilistic seismic performance evaluation of contemporary steel dampers and rubber bumpers in reducing seismic demands and achieving movement control between reinforced concrete adjacent bridges present in a medium seismic region using inelastic dynamic simulations. The numerical modeling approaches of the selected retrofit strategies were validated against the hysteretic response of previous experimental studies. The numerically validated retrofit measures are subsequently implemented in the three-dimensional fiber-based model of the reference bridge to assess the enhancement in seismic performance under different seismic scenarios. The preliminary assessment involving the eigenvalue analysis indicated that the fundamental natural period of vibration of the bridge's superstructure shortened by 26% due to the implementation of the energy-dissipating steel dampers and rubber bumpers. A detailed assessment involving multi-record incremental dynamic analyses was performed by subjecting the reference bridge to a diverse range of earthquake records. The fragility relationships obtained from this comprehensive assessment revealed that the steel dampers primarily contributed to reducing bearing displacement demands, with a marginal effect on the pounding force between the adjacent bridges. Installing rubber bumpers in the separation gap between the adjacent bridges remarkably minimized PF. This study thus offers insights into the effective contemporary retrofit measures for enhancing seismic performance and mitigating movement between RC adjacent bridges.

Acknowledgments

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