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Seismic Performance Enhancement of RC Bridge Bents Using Advanced Retrofit Techniques

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* -** Recent seismic events have revealed an increased vulnerability of substandard reinforced concrete (RC) bridges to various damage modes, underscoring the essential need for seismic retrofitting. This study thus investigates the effectiveness of modern retrofit approaches to upgrade the seismic performance of RC bridge bents, mainly focusing on high-performance concrete jackets and buckling restrained braces. The chosen retrofit measures are intended to mitigate the curvature ductility demands of substandard RC bridge piers. The adopted retrofit approaches are verified against previous experimental results through detailed three-dimensional fiber-based modeling and implemented in a representative multi-span RC bridge in a medium seismicity region. The inelastic dynamic response of the case study bridge bents before and after retrofitting with the adopted seismic mitigation measures is assessed under different seismic scenarios. The relative effectiveness of the retrofit measures in minimizing the curvature ductility of the bridge columns is evaluated through fragility analyses. The seismic assessment results indicate that both the adopted mitigation measures are comparable in reducing the probability of damage related to bridge bents. However, the adopted measure that integrates seismic performance and cost for the buckling restrained braces is almost 40% to 80% higher than that of the other alternative under the effect of different seismic scenarios, confirming its preference among the two retrofit alternatives. This study thus offers insight into selecting effective and economical retrofit solutions for upgrading RC bridge bents, thus ensuring the bridge's continuous functionality.

***Keywords*:** RC bents, Upgrading bridges, Fragility analysis, Seismic risk mitigation.

1. Introduction

Previous seismic performance evaluation studies indicated that pre-code bridges that do not comply with current seismic design standards are prone to various failure modes under strong seismic actions, demonstrating their need for retrofitting [1, 2]. Hence, seismic retrofitting aims to mitigate the damage modes of substandard bridges, considering them as critical structures [3]. Seismic performance improvement of reinforced concrete (RC) structures can be achieved through local or global retrofit methods such as high-performance concrete (HPC) jacketing and the addition of steel braces, respectively [4, 5]. HPC jacketing is recognized as an effective retrofit option for enhancing the strength and ductility of RC bridges and buildings [6-8]. Moreover, HPC-jacketed RC piers demonstrate improved resilience under sustained loads and mitigate concrete spalling due to the presence of fibers [9]. Moreover, conventional buckling-restrained braces (BRBs) demonstrate good energy dissipation capabilities, but they are limited by significant residual deformations during severe seismic events. This drawback can be addressed by employing self-centering (SC) BRBs, characterized by a flag-shaped hysteresis response that minimizes residual deformation [10, 11]. Hence, this paper focuses on assessing the performance of HPC and SC-BRB in upgrading RC bridge bents located in a region vulnerable to multiple seismic scenarios and prioritizing the retrofit alternatives through seismic performance-cost indicators.

2. Selection and Modeling of Case Study Structure

The chosen reference structure for this study is a multi-span RC bridge located in Al Ain City, United Arab Emirates, a low-to-medium seismic area as per previous seismic hazard studies [12]. Based on its construction period, the reference structure is classified as a substandard bridge, highlighting its vulnerability to damage modes under different seismic scenarios. The bridge superstructure involves a five-span RC deck supported over a substructure comprising four sets of bridge bents. The superstructure is supported on the bridge bents through elastomeric bearings, as depicted in Fig. 1. The circular columns' diameter and clear height are 1 m and 4.5 m, respectively. A detailed three-dimensional (3D) model of the entire bridge is developed using fiber-based analysis software, as shown in Fig. 1 [13-15]. A uniaxial confined concrete model idealizes the structural components with a compressive strength of 25 MPa [16]. The reinforcing steel is modeled using a uniaxial stress-strain model proposed by Menegotto and Pinto [17]. The bridge columns and the cap beams are idealized using inelastic displacement-based beam-column elements. Rigid arms represent the high rigidity of the beam-column joints.

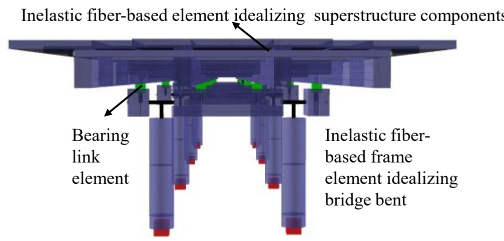

Fig. 1: View of the representative bridge bent (left) and its numerical model (right).

3. Modeling and Implementation of Retrofit Techniques

The modeling approaches of the chosen retrofit measures are verified against existing experimental results to ensure a reliable performance evaluation. A detailed fiber-based modeling approach involving the HPC jacketing technique is verified in the current study using a quasi-static experiment on the cyclic performance of a circular RC bridge pier retrofitted with this high-performance material [6]. Similarly, the SC-BRB modeling approach is also verified using previous experimental results of an RC bridge bent equipped with SC-BRB [10]. The hysteretic behavior obtained from the current study demonstrated a strong correlation with the previous experiment results, validating the adopted modeling approaches of the retrofit technique (Fig. 2).

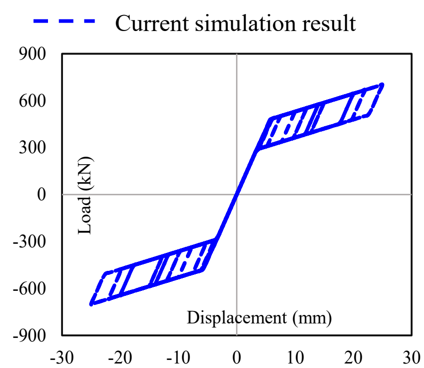

Fig. 2: Modeling of the SC-BRB retrofit.

The validated retrofit measures are implemented on the selected reference bridge bent to assess their effectiveness on seismic performance enhancement. For the HPC retrofit measure, a jacket thickness of 80 mm with a cube compressive strength of 110 MPa is applied to the entire height of all columns of the reference bridge, as illustrated in Fig. 3(a). An additional external longitudinal reinforcement of 12 mm bars and transverse reinforcement of 10 mm bars in a spiral pattern is utilized. The HPC retrofit measure is designed to achieve a comparable initial stiffness and lateral capacity with the SC-BRB retrofitted bents, enabling a fair comparison between them. A uniaxial high-strength concrete model represents the HPC jacket material [18]. The SC-BRB retrofit is implemented to each bridge bent in the transverse direction, as shown in Fig. 3(b). The steel brace is idealized using an elastic frame element featuring large axial stiffness properties, and the SC element is modeled using a uniaxial response curve placed at the intersection of the two rigid arm braces [13, 19]. After retrofit measures are applied, the reference bridge is assessed for seismic performance improvement through incremental dynamic analysis (IDA) procedure, as subsequently discussed.

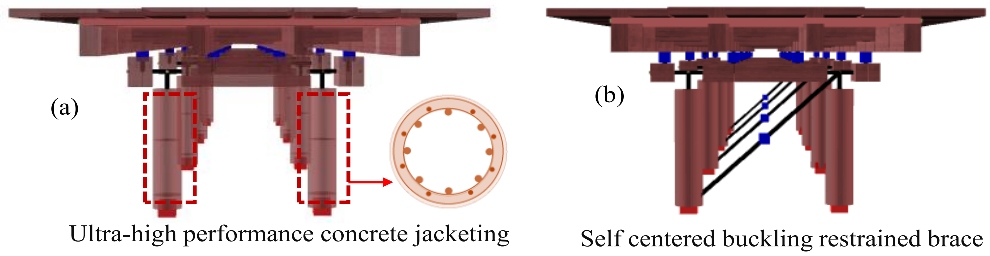

Fig. 3: Implementing retrofit measures on the reference bridge: (a) HPC jacketing, and (b) SC-BRB retrofit.

4. Incremental Dynamic Analysis

To assess the seismic response of the case study structure, IDAs were undertaken using seven long-period (LP) and seven short-period (SP) earthquake records [20]. The LP seismic records are scaled to an intensity level starting from half the design intensity (i.e., 0.5D) to 3.5 times the design intensity (i.e., 0.08g to 0.56g) with an increment of 0.5D. The SP 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 earthquake records are applied in the transverse direction of the bridge, and the corresponding fragility relationships are obtained [21]. Four levels of damage states, namely slight (SL), moderate (MO), extensive (EX), and complete (CO), are adopted to assess the probability of exceeding curvature ductility (CD) demands for the unretrofitted and retrofitted bridge. Figs. 4(a) and 5(a) illustrate that the probability of exceeding different limit states is higher for the unretrofitted bridge, highlighting its vulnerability to CD damage. The IDA curves in Figs. 4 and 5 demonstrate a notable reduction in CD under the LP and SP scenarios across all four limit states due to the implemented retrofit measures. However, the SC-BRB is slightly more effective in mitigating CD than the HPC retrofit technique because the CD demand has been significantly reduced within all limit states, particularly below the CO limit state, as shown in Figs. 4(c) and 5(c).

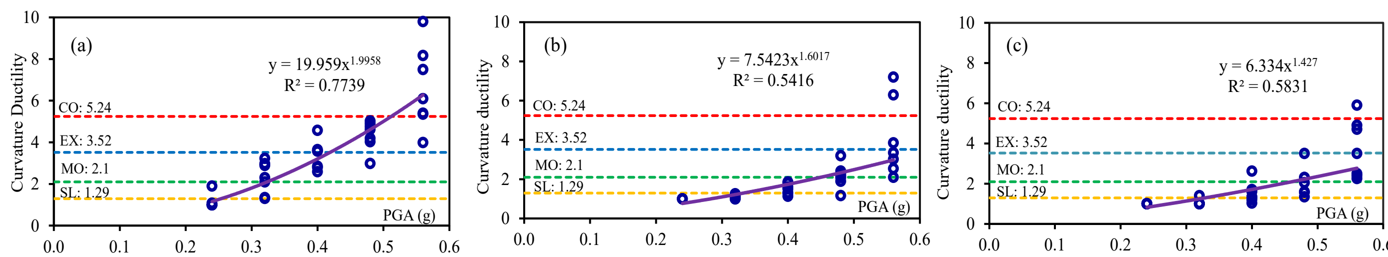

Fig. 4: Regression analysis results of the reference bridge under long-period seismic records: (a) unretrofitted bridge, (b) bridge with HPC jacket, and (c) bridge with SC-BRB.

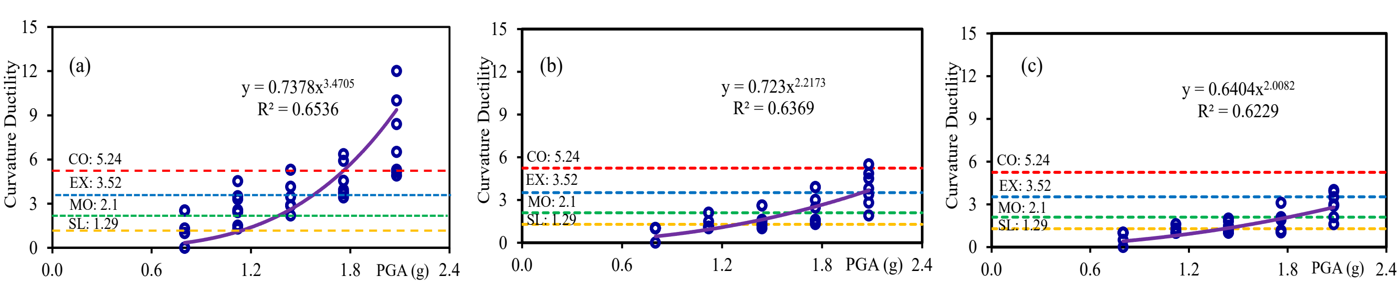

Fig. 5: Regression analysis results of the reference bridge under short-period seismic records: (a) unretrofitted bridge, (b) bridge with HPC jacket, and (c) bridge with SC-BRB.

5. Selection of Bent Retrofit Techniques using Seismic Performance and Cost

An effective structural performance measure is essential for evaluating the effectiveness of retrofitting measures using fragility curves. The adopted structural performance measure incorporates the median intensity measure values derived from the fragility curves of unretrofitted and retrofitted bridges, along with a weighting factor that accounts for the standard deviation at each limit state [4, 21, 22]. The implementation of the SC-BRB system demonstrates a higher seismic performance than the application of HPC jackets, as shown in Fig. 6. After computing the structural performance, a systematic ranking process is employed to determine the most effective and economically viable retrofit technique by incorporating the costs of retrofit options along with the structural performance. The cost of HPC materials and the bracing system are estimated based on information procured from suppliers and manufacturers. Fig. 6 shows the results of integrating performance and cost (PC) for the adopted retrofit measures. Fig.6 shows that the HPC jacketing has the least PC due to its high cost. It is confirmed from the presented results that the SC-BRB has a higher SCI than HPC by almost 40% and 80% under the LP and SP earthquake scenarios, respectively, confirming the SC-BRB's preference among the considered retrofit measures.

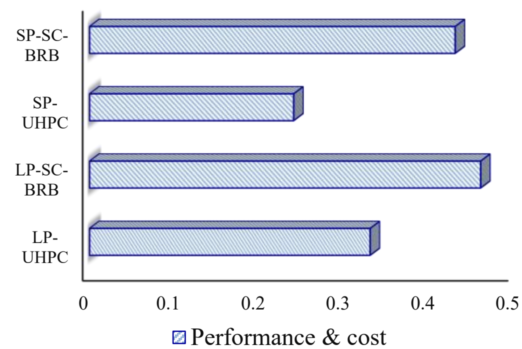

Fig. 6: Selection of retrofit techniques based on seismic performance and cost under LP and SP earthquake scenarios.

6. Conclusion

This study evaluated the effectiveness of contemporary ultra-high-performance jackets and buckling restrained braces in upgrading the seismic performance of reinforced concrete bridge bents present in a seismic zone vulnerable to multiple seismic scenarios using inelastic dynamic response simulation. The modeling approaches of the selected retrofit strategies were validated against the hysteretic responses of previous experimental studies and then implemented in the three-dimensional fiber-based bridge model to assess their relative seismic performance. The fragility curves obtained from multi-record incremental dynamic analysis confirmed that both retrofit techniques effectively reduced curvature ductility demands of the substandard bridge bents. While the probabilistic assessment study indicated a comparable seismic performance enhancement in the substandard bridge due to the adopted two retrofit options, the buckling restrained braces demonstrated a seismic performance cost of 40%-80% higher than the other alternative, establishing it as the preferred retrofit option. This study thus helps to select an effective and economical retrofit strategy for mitigating the seismic risk of RC bridge bents.

Acknowledgments

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