SEISMIC RETROFIT OF SUBSTANDARD RC BRIDGES USING CONTEMPORARY MITIGATION MEASURES

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As essential infrastructure components, existing substandard bridges may cause significant economic losses at the urban scale as they are prone to different damage modes under seismic excitations. Due to the large number of existing RC bridges in earthquake-prone regions and the continuous updates in seismic design criteria, there is increasing interest in developing effective seismic retrofit techniques for enhancing the performance of these structures. This study thus investigates the effectiveness of contemporary retrofit measures for upgrading the seismic performance of RC bridges, namely ultra-high-performance concrete (UHPC) jackets and self-centering energy dissipating (SCED) braces. Detailed fiber-based numerical models are developed for scaled RC bridge substructures retrofitted with the adopted mitigation measures. The hysteretic behavior of the bridge substructures from quasi-static cyclic loading experiments conducted in previous studies is utilized to verify the developed fiber-based models. The validated modeling approaches of retrofit strategies are then applied to an old benchmark bridge located in a medium seismicity zone. The inelastic response of the benchmark bridge substructure before and after the retrofit with different mitigation measures is assessed using the verified fiber-based numerical models. The results demonstrate that the retrofit measures increased the lateral strength of the bridge bent by 37.5%. Also, 10% improved ductility was observed in the UHPC retrofitted bent. This performance assessment study enabled the selection of effective measures to mitigate the vulnerability of substandard bridge members to ensure their post-earthquake functionality.

Keywords: Old bridges, Fiber-based modeling, Dynamic response simulation, Retrofit measures.

1 INTRODUCTION

Bridges are vital connecting components of transportation networks. However, many RC bridges serving in earthquake-prone regions were constructed decades ago and hence primarily do not meet the requirements of current seismic design standards. Furthermore, observations from past earthquakes show that pre-seismic code bridge piers are vulnerable to different damage modes under strong seismic actions (Elnashai and Mwafy 2022). Hence, there arises a need for seismic retrofit of such components to mitigate the earthquake risk. The objective of seismic retrofitting in bridge structures is to maintain the structure’s functionality, particularly for critical and essential bridges. Retrofitting can be divided into local retrofit, which aims to improve the strength and ductility of structural members, and global retrofit, which operates on the structure as a whole and may include the addition of structural elements such as steel braces or replacing bridge bearings.
RC jacketing technique has been extensively used for retrofitting bridge substructures. This conventional retrofit approach improves bridge piers’ flexural strength, ductility, and energy dissipation capacity. However, the larger thickness of RC jackets leads to high dead loads and space reduction. Also, increasing the stiffness of structural members through RC jackets may have several drawbacks if not required to control the lateral drift, as it increases seismic demands. Therefore, ultra-high-performance concrete (UHPC) material is recently recommended as an effective retrofit alternative for buildings and bridges. It provides high strength, ductility, and durability with a small jacket thickness and thus occupies less space (Joseph et al. 2022, Yuan et al. 2022). Recent experimental studies concluded that bridge piers retrofitted with UHPC jackets exhibited high lateral strength, improved ductility, reduced drift and residual displacement, and enhanced seismic resilience (e.g., Shao et al. 2021). However, most previous studies focused on applying UHPC jackets without additional reinforcement. In addition, limited studies focused on the numerical investigation of bridges representing the existing infrastructure in different earthquake-prone regions using the UHPC retrofit. Hence, a detailed numerical investigation of UHPC retrofitted bridge substructure, particularly with added external reinforcement, would address the above research gap.

Furthermore, buckling restrained braces (BRBs) are used in moment-resisting frame structures to serve as energy dissipation members due to their stable hysteretic behavior. However, excessive residual deformation is one of the drawbacks of conventional BRBs during large earthquakes. This shortcoming can be mitigated using self-centering BRBs, which exhibit a flag-shaped hysteresis response with reduced residual deformation (Dong et al. 2020). Previous numerical investigations demonstrated the improved seismic performance of RC buildings with different structural systems when retrofitted with energy-dissipative SC-BRBs (Joseph et al. 2022). However, there is a need for more seismic performance assessment studies, particularly for substandard bridges retrofitted with contemporary techniques in different seismic regions. Based on the brief literature review, the main objective of this study is to investigate the effectiveness of the UHPC and SC-BRB retrofit measures for an existing pre-seismic code bridge in the United Arab Emirates (UAE), the selected study area to represent moderate seismic regions.

2 MODELLING VERIFICATION OF RETROFITTED SUBSTRUCTURES USING UHPC AND SC-BRB

The modeling approaches of the selected retrofit measures in the present study must be verified first against available experimental results to arrive at a reliable assessment of their effectiveness when implemented to existing bridge bents. Therefore, a detailed fiber-based modeling approach that involves the UHPC 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 UHPC (Yuan et al. 2022). The tested specimen had a clear height and diameter of 1300 mm and 320 mm, respectively, as shown in Figure 1. The UHPC compressive strength was 110.6 MPa. The thickness of the UHPC jacket was 50 mm, which was applied for the plastic hinge region (i.e., 600 mm from the base). The adopted retrofit technique’s modeling verification is carried out in the present study through a versatile fiber-based analysis platform (Seismosoft 2022). The columns and cap beam are modeled using an inelastic displacement-based frame element. The connection of the RC pier with the base block is modeled through a rigid arm represented by an elastic frame element. A constant axial load of 250 kN is applied at the top of the pier to simulate the superstructure weight. The quasi-static cyclic loading described in the experimental study is applied laterally in a displacement control mode to the pier top. The backbone curve of the UHPC retrofitted bent is obtained by plotting the peak response of the force-displacement
diagram, as shown in Figure 2(a). The backbone curve is then compared with previous experimental and numerical results (Yuan et al. 2022). It is shown that the obtained results correlate well with the previous quasi-static cyclic experiment, which validates the adopted fiber-based modeling approach of the UHPC retrofit in the present study.

![Figure 1. UHPC-retrofitted bridge pier used for modeling verification (Yuan et al. 2022).](image)

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![Figure 2. Comparisons of backbone curves obtained from numerical and experimental results for retrofitted bridge specimens: (a) UHPC retrofit, and (b) SC-BRB retrofit.](image)

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An experimental study performed on two RC column bridge bent equipped with SC-BRB is adopted in the present study for verifying the modeling approach of the SC-BRB retrofit measure (Dong et al. 2020). As shown in Figure 3, the bent comprised two circular piers of 1600 mm in clear height and 300 mm in diameter. The cross-sectional dimension of the cap beam was 400 mm x 400 mm and 3600 mm long. The SC-BRB added to the bent consisted of BRB as the energy dissipation system and a self-centering element. To validate the flag-shaped hysteretic behavior of the SC-BRB, the brace is modeled in the current study using a link element that exhibits a uniaxial response behavior (Seismosoft 2022). The parameters used to model the SC element are obtained from the previous experimental results. These include initial stiffness, post-yield stiffness, activation force, energy dissipation ratio, slip displacement, and displacement at the start of stiffness increase (Dong et al. 2020). A displacement-controlled cyclic loading was applied to the retrofitted bridge bent to obtain its hysteretic response. A comparison of the backbone curves obtained from the present study and those from the previous experimental and
numerical study is shown in Figure 2(b). The comparable results obtained from the fiber-based numerical model developed in the present study verify the adopted modeling approach and enable using it for the assessment of the selected benchmark bridge, as discussed hereafter.

![Figure 3. SC-BRB retrofitted bridge bent used for modeling verification study (Dong et al. 2020).](image)

### 3 PERFORMANCE ASSESSMENT OF EXISTING AND RETROFITTED BRIDGE SUBSTRUCTURE

#### 3.1 Performance Assessment of Benchmark Bridge Substructure before and after Retrofit

The benchmark bridge selected for this study is located in a medium seismicity zone, represented by Al-Ain city, UAE (Ghazal and Mwafy 2022). The superstructure is a five-span RC deck supported on RC girders. The substructure comprises four bents; each spaced 14 m apart. The columns of the bridge bent are circular and have a cross-section of 1.0 m in diameter and a clear height of 4.5 m. The cap beam has a cross-section of 1.3 m x 1.1 m. The concrete compressive strength is 24 MPa, UHPC compressive strength is 88 MPa, and the main steel yield strength is 420 MPa. Figure 4 shows the benchmark bridge substructure.

Fiber-based models of the benchmark bridge bent are developed to predict the lateral load-carrying capacity of the retrofitted substructure in the transverse direction using static pushover analysis. The inelastic analysis results are used to trace the progress of local damage modes, such as the reinforcing steel yielding and concrete crushing, and to capture the global response before and after the retrofit. The UHPC retrofit measure is applied to the bent columns for the full height. Excluding the concrete cover of the existing column, a jacket thickness of 80 mm is used. External longitudinal reinforcement of 12 mm diameter and transverse rebars of 10 mm diameter at 50 mm spacing are used to retrofit columns. Moreover, the SC-BRB retrofit measure is implemented to the existing bent in a transverse direction, and the verified self-centering element is coupled to the center of the rigid brace element, as shown in Figure 4. Figure 5 illustrates the results of the inelastic pushover analysis in the transverse direction for the un-retrofitted bent and the retrofitted alternatives. It is observed that the SC-BRB retrofit system provided comparable initial stiffness and ultimate strength to those obtained from the other retrofit counterpart. However, the SC-BRB retrofit approach provided limited ductility due to exceeding the BRB steel core capacity at a displacement of 90 mm. On the other hand, the UHPC retrofit measure provided notably better ductility than the SC-BRB retrofit technique.

Regarding lateral strength capacity, the ultimate strength of the un-retrofitted bent is 1599 kN, while for the UHPC and SC-BRB retrofit alternatives, it is 2203 kN and 2205 kN, respectively. Both the adopted retrofit methods increase the existing structure’s capacity by almost 37.5%. The monitored local damage indices include the plastic hinge formation and
concrete crushing for confined and unconfined concrete. For the existing structure, the steel reinforcement strain of the pier reaches the yield strain at 14 mm top displacement. For the retrofitted substructure, the first steel yielding is observed at a top displacement of 12.3 mm and 13.3 mm for SC-BRB and UHPC retrofit, respectively. The confined concrete crushing occurs at a top displacement of 161 mm and 169 mm for the un-retrofitted and UHPC retrofitted bents, respectively. Buckling of longitudinal rebars was not observed since the small spacings of transverse reinforcement provided effective confinement and prevented buckling. The inelastic performance assessment generally reflected the effectiveness of the adopted retrofit schemes in improving lateral strength and delaying local damage modes.

Figure 4. Description of benchmark bridge bent and its fiber-based model when retrofitted with SC-BRB.

Figure 5. Capacity curves of un-retrofitted and retrofitted bents using UHPC and SC-BRB.

3.2 Comparison of Retrofit Alternatives

Figure 6 shows the overstrength factors associated with un-retrofitted bent and its retrofitted alternatives. The presented overstrength factors are based on the calculated seismic design forces for two cases: whether the bridge is considered essential or critical. It is shown that the overstrength factors of the existing bridge bent have improved after the retrofit process and are almost comparable for both retrofit methods. Moreover, Figure 6 depicts the ductility factors, defined as the ratio of ultimate to yield displacement. The UHPC retrofitted bent exhibited higher ductility than the existing and SC-BRB retrofitted bent. As previously highlighted, the limited ductility of the bent retrofitted with SC-BRB is due to exceeding the BRB steel core capacity.
Figure 6. Overstrength and ductility factors for the existing and retrofitted bends.

4 CONCLUSIONS

This study investigated the effectiveness of contemporary retrofit measures, namely UHPC jackets and SC braces, for upgrading the seismic performance of RC bridge substructure using verified fiber-based numerical models. The hysteretic behavior of the adopted retrofit strategies was captured by verifying their numerical modeling approach against previous quasi-static cyclic experiments. Inelastic pushover analyses were carried out for a benchmark bridge substructure and its retrofitted alternatives. The predicted capacity curves confirmed that both retrofit measures upgraded the lateral strength of the existing bent by 37.5%. In addition, the UHPC retrofit measure proved more ductile than the SC-BRB retrofit alternative. Thus, based on this study, it is concluded that the UHPC retrofit strategy effectively enhances the substructure’s lateral capacity. Additional seismic vulnerability analysis using sets of earthquake records representing different seismic scenarios is recommended to confirm the retrofit techniques’ effectiveness and ensure the substandard bridges’ functionality in the study region.

Acknowledgments

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References