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# A Systematic Framework for the Seismic Risk Management of RC Bridges Using Various Retrofit Strategies

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***Abstract*** – Reinforced concrete (RC) bridges are vital components of the transportation infrastructure. However, several existing bridges may fail to meet the target performance objectives of current seismic design standards. Past earthquakes have underscored the vulnerability of substandard bridges to damage modes such as pounding and curvature ductility demands, emphasizing the critical need for seismic retrofitting. This paper proposes a systematic methodology for selecting individual and hybrid retrofit strategies for the seismic risk management of substandard RC bridges. This framework is applied to a benchmark multi-span RC bridge representing a large bridge inventory in a medium seismicity study region. The proposed framework selects retrofit measures that mitigate various damage modes, including excessive bearing displacement, pounding between nearby bridges, and significant curvature ductility demands in bridge bents. The adopted retrofit approaches are verified against previous experimental results through detailed three-dimensional fiber-based modeling and implemented in the representative bridge to evaluate the dynamic response behavior of the existing and retrofitted bridges. The nearby bridges' lateral capacity is initially investigated to assess the retrofit options by analyzing various local damage indicators. Fragility analyses are then performed under different seismic scenarios to compare the effectiveness of the proposed retrofit strategies. Finally, a versatile seismic performance-cost indicator is employed to prioritize the retrofit alternatives and to propose a hybrid retrofit strategy that effectively addresses various damage modes inherent in the substandard bridge and ensures the safety and serviceability of existing RC bridges.

***Keywords*****:** Seismic risk assessment, Incremental dynamic analysis, Fragility analysis, Retrofit.

## 1. Introduction

Multispan highway bridges are strategic elements in modern transportation networks that are required to ensure their functionality during and after earthquakes. However, past earthquake events have shown that substandard bridges constructed without considering modern seismic design guidelines are prone to severe damage or collapse during intense seismic events [1, 2]. While various seismic retrofit techniques for upgrading reinforced concrete (RC) bridges are outlined in design standards and guidelines, there is a pressing need for a straightforward and systematic approach to identify the most suitable retrofit solutions for the seismic risk management of complex bridges vulnerable to multiple damage modes [1, 3]. Previous studies have conducted extensive earthquake vulnerability assessments and suggested risk-mitigation strategies, emphasizing the need for an interdisciplinary approach that includes hazard characterization, evaluation of physical damage to exposed structures, and assessment of socio-economic impacts [1, 4, 5]. Moreover, previous seismic risk mitigation studies have primarily focused on assessing the performance of individual retrofit techniques for upgrading substandard bridges or buildings using fragility analysis [6-8]. However, relying only on fragility functions to select the optimal seismic retrofit solutions is insufficient, as they do not account for cost considerations [9, 10]. Hence, this study focuses on proposing a systematic framework for selecting an effective hybrid retrofit measure for managing the seismic risk of the substandard bridge inventory in a region vulnerable to multiple seismic scenarios, considering the seismic performance and retrofit cost.

## 2. Selection of Reference Structure Representing Bridge Inventory

Based on a detailed survey of a study area susceptible to various seismic scenarios represented by the Al-Ain City, United Arab Emirates (UAE), a benchmark bridge is chosen. Recent seismic hazard assessment studies classified the study region as a low to medium seismic zone where the study area is vulnerable to near-field (NF) and far-field (FF) earthquake ground motions [9, 11, 12]. In the present study, a database of bridges is compiled initially using satellite imageries, which revealed that most of the structures are multi-span nearby RC bridges with different types of substructures [13]. The benchmark bridge is chosen from the database after site inspections. Since the selected study area was previously categorized as a non-seismic zone, the structures constructed before the 2000s were considered pre-seismic code structures, highlighting their vulnerability to various damage modes under the effect of different seismic scenarios [14].

To develop fragility functions, the inelastic dynamic simulations utilize a diverse collection of input ground motions representative of the study area and the anticipated seismic scenarios. The ground motion selection includes fourteen earthquake records, which comprise seven NF and seven FF ground motions, to assess the probability of the benchmark bridge exceeding a range of performance limit states [11]. The earthquake records are sourced from the European Strong Motion and Pacific Earthquake Engineering Research Center databases [15, 16]. As shown in Fig. 1(a), the average of the seven selected records for the FF seismic scenario aligns closely with the mean of several input ground motions used in previous seismic assessment studies for the study region [12, 17, 18]. Therefore, the fourteen records chosen in this study effectively represent the expected seismic scenarios in the study area while optimizing computational efficiency for the probabilistic seismic evaluation.

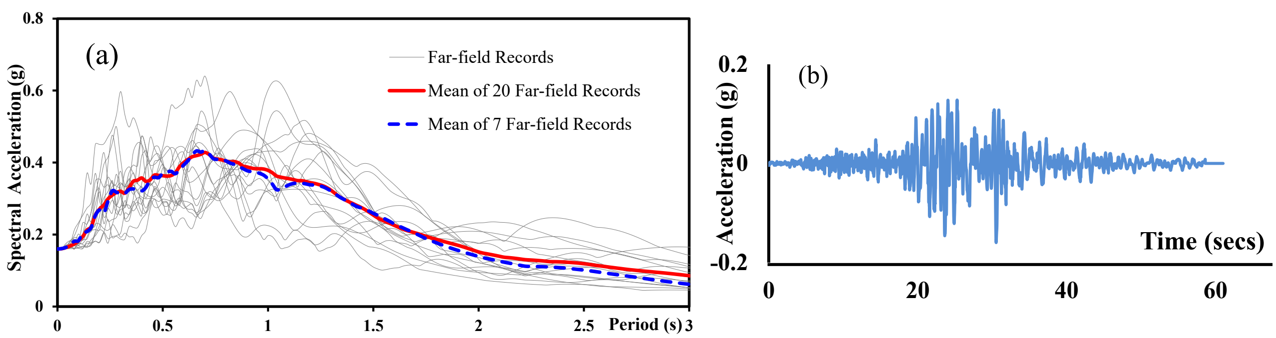


Fig. 1: Earthquake records normalized to the design intensity: (a) elastic response spectra of FF ground motions used for the seismic assessment; (b) acceleration history of a representative FF earthquake record.

## 3. General Description of the Reference Bridge and Seismic Risk Mitigation Measures

The benchmark bridge comprises two identical structures placed beside to each other, separated by a narrow 20 mm gap. The superstructure consists of a five-span RC deck supported by RC girders, which rest on the substructure through elastomeric bearings. The substructure includes four sets of bents arranged 14 m apart along the longitudinal direction, as depicted in Fig. 2. Each bridge bent has two circular columns with a diameter of 1.0 m and a clear height of 4.5 m.

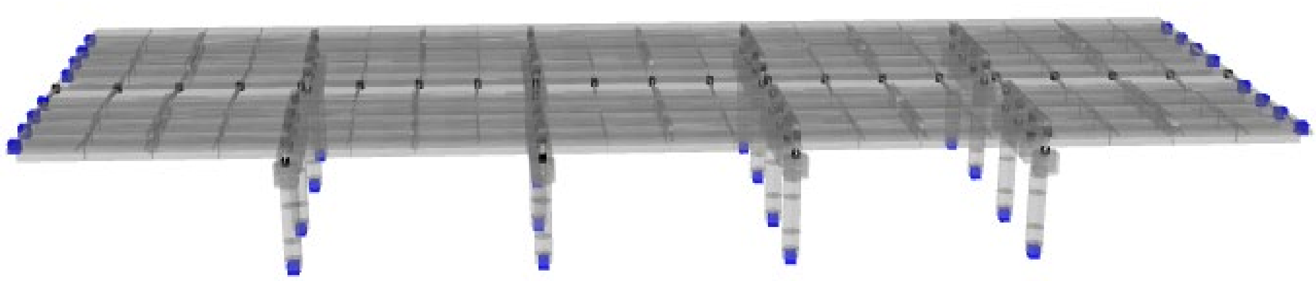

Fig. 2: Three-dimensional fiber-based numerical model of the reference bridge.

Seismic performance improvement of existing substandard bridges can be categorized into three aspects: decreasing seismic demands, controlling movement between nearby bridges, and enhancing seismic performance. This study employs energy-dissipating steel dampers along with the existing bridge bearings to lower excessive bearing displacements, thereby reducing the overall seismic demands on the bridge. Rubber bumpers are utilized as shock absorbers to control movement between nearby bridges, effectively reducing pounding force demands. Moreover, ultra-high-performance concrete (UHPC) jacketing and self-centering buckling-restrained braces (SC-BRB) are implemented to address the curvature ductility demands of the bridge piers. Based on the probabilistic seismic performance assessment of the retrofitted nearby bridges with each of the adopted mitigation strategies and their contribution in mitigating different damage modes sufficiently, a hybrid retrofit measure is proposed following the systematic methodology depicted in Fig. 3.

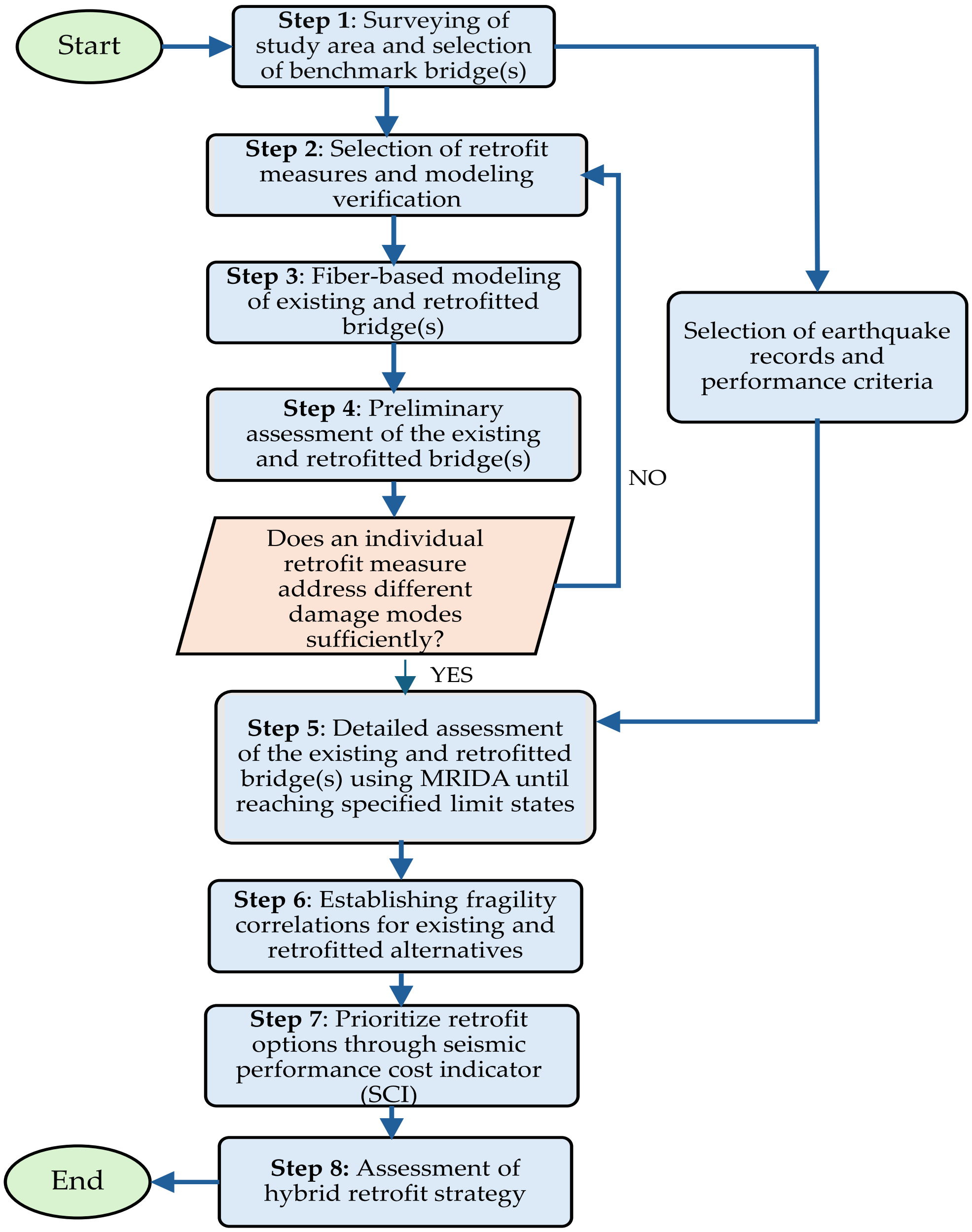


Fig. 3: The systematic methodology for upgrading existing substandard RC bridges.

## 4. Methodology for Selecting Seismic Risk Management Alternatives

The adopted framework to devise an efficient mitigation strategy for enhancing the seismic performance of substandard RC bridges is shown in Fig. 3. The procedure starts by surveying the study area to select a representative bridge to be used in the probabilistic seismic assessment as previously discussed in Section 2 (Step 1). Since the benchmark bridge is vulnerable to different damage modes, an extensive literature review selects suitable retrofit measures to address the damages. The adopted mitigation measures idealization is verified by comparing their static cyclic test results of fiber-based numerical models with the hysteretic behavior obtained from previous experimental studies (Step 2). Detailed fiber-based three-dimensional models of selected nearby bridges are developed to assess the inelastic behavior before and after retrofitting with the verified retrofit measures (Step 3). It is worth noting that the entire benchmark structure is modeled using an experimentally verified fiber-based analysis platform [4, 12, 19, 20]. Free vibration analysis and incremental static pushover analysis are conducted to preliminarily evaluate the changes in dynamic characteristics and enhancements in lateral strength of the benchmark bridges through the adopted retrofit alternatives (Step 4). Several global damage indices, such as lateral strength, stiffness, and ductility, are monitored to obtain an initial decision on the retrofit measure's performance. If the selected individual retrofit measure does not address the damage mode sufficiently, then the process is redirected to Step 2 to select additional retrofit measures.

Detailed probabilistic seismic performance assessments are conducted by performing multi-record incremental dynamic analyses (MRIDA) using diverse earthquake records for the un-retrofitted and retrofitted bridges (Step 5). Fragility relationships are developed under different seismic scenarios to assess the relative performance of the adopted retrofit schemes and to evaluate the likelihood of exceeding the bridge's seismic capacity (Step 6). A versatile seismic performance-cost indicator is adopted to prioritize the seismic risk mitigation alternatives directed to the substructure [10]. In addition to the seismic performance enhancement, the cost of the adopted retrofit strategies is also addressed by integrating economic considerations and seismic performance into a seismic performance cost indicator (SCI) to determine the optimal retrofit option (Step 7). In order to exploit the benefits of different retrofit strategies and address various damage modes sufficiently, a hybrid retrofit approach is proposed as an effective and economical enhancement technique for the seismic performance of the substandard multi-span bridges, as subsequently discussed in Section 5 (Step 8).

## 5. Selection of Hybrid Retrofitting for Delaying Various Damage Modes of RC Bridges

Probabilistic fragility functions are developed through a series of inelastic multi-step dynamic simulations conducted on the substandard bridge and its retrofitted alternatives using fourteen earthquake records. Four levels of damage states, namely slight (SL), moderate (MO), extensive (EX), and complete (CO), are defined to evaluate the likelihood of exceeding seismic demands. The probabilistic seismic performance assessment of various individual retrofit options, such as the SC-BRB, UHPC jacketing, steel dampers, and rubber bumpers, revealed that each strategy primarily improves the seismic performance of a specific demand parameter only. The UHPC jacketing and SC-BRB specifically alleviate curvature ductility (CD) for bridge bents [21, 22]. The steel dampers decrease bearing displacement (BD), while the rubber bumper reduces the pounding force (PF) between the nearby bridges.

As depicted in Fig. 4(a), the SC-BRB is ineffective in mitigating PF between nearby bridges. The UHPC jacketing and SC-BRB do not contribute to reducing BD or PF between the nearby bridges. The steel dampers and rubber bumpers do not address CD-related damage in bridge bents. Therefore, a hybrid retrofit approach is proposed to exploit the benefits of different retrofit strategies and address various damage modes sufficiently. The SCI combined structural performance with retrofit cost considerations and facilitated the selection of the economically optimal SC-BRB retrofit option with steel dampers and rubber bumpers as the hybrid mitigation strategy to evaluate its effectiveness in mitigating various damage modes inherent in nearby bridges. MRIDA is performed on the benchmark bridge using this hybrid measure, and fragility curves are generated based on the MRIDA results obtained. Fig. 4(b) highlights the higher vulnerability of the un-retrofitted benchmark bridge to PF demand while demonstrating the remarkable effectiveness of the hybrid retrofit strategy in reducing PF demands across all limit states. Similarly, the hybrid retrofit strategy effectively decreased other damage states, including CD and BD demands.

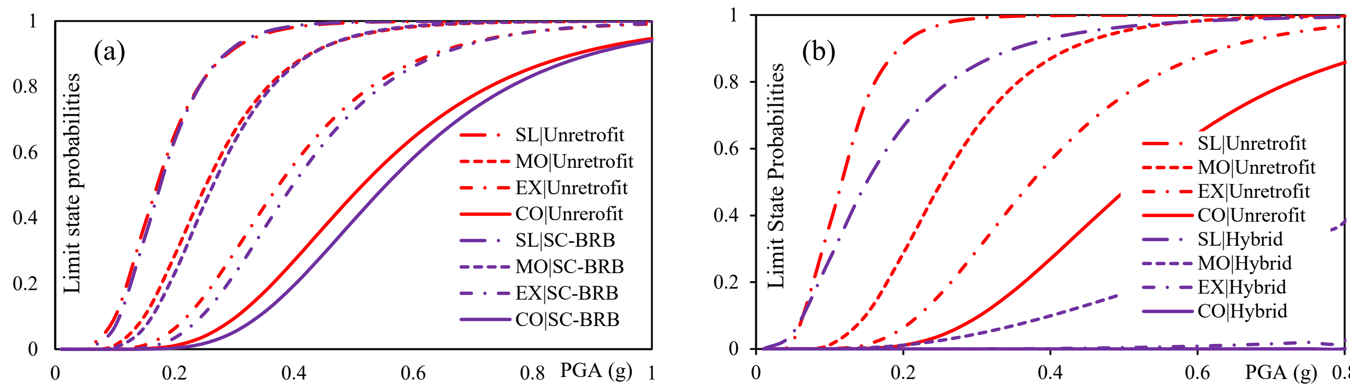


Fig. 4: Sample results of fragility functions for the un-retrofitted and retrofitted bridges pounding force demands under FF scenario: (a) effect of the individual retrofit measure, and (b) effect of the hybrid retrofit measure.

## 6. Conclusions

This study proposed a systematic framework for the seismic risk management of substandard reinforced concrete (RC) bridges vulnerable to various damage modes through individual and hybrid retrofit measures based on their seismic performance and cost. The proposed methodology consists of various steps involving selecting and verifying suitable retrofit techniques, which are then applied to a representative substandard bridge representing the bridge inventory in a medium seismicity region. Preliminary assessment methods such as the eigenvalue analysis and inelastic pushover analysis served as initial validation for the performance assessment of different retrofit strategies of the benchmark bridge. Detailed seismic assessment involving the multi-record incremental dynamic analysis demonstrated the effectiveness of individual and hybrid retrofit measures in reducing various damage modes inherent in substandard RC nearby bridges. While the conclusions of this research study apply to RC multi-span nearby bridge inventory in the study region, some generalities for other RC bridges can be claimed as the adopted seismic assessment methodology involving detailed 3D models of a benchmark bridge and different retrofit techniques validated against experimental results to realistically select the most effective and economic seismic risk mitigation strategy to ensure a functioning transportation network post-earthquake.

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