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A Systematic Methodology for Prioritizing Seismic Retrofit Alternatives

Roshen Joseph[1], Aman Mwafy[1], M. Shahria Alam [2]
[1] Dept. of Civil and Environmental Engineering, United Arab Emirates University
Al Ain, UAE
201990208@uaeu.ac.ae; amanmwafy@uaeu.ac.ae
[2] School of Engineering, the University of British Columbia
Kelowna, BC, Canada
shahria.alam@ubc.ca

Abstract **–** This paper proposes a systematic methodology for prioritizing seismic retrofit alternatives by considering their seismic performance and cost. The framework was applied to retrofit substandard buildings with structural systems common to a medium seismicity region. The proposed seismic assessment and retrofit methodology starts by evaluating the demand-to-capacity (D/C) ratios of the as-built structure and its retrofitted alternatives using 3D finite element models and code-prescribed analysis procedures in line with the region's seismic design criteria. After selecting suitable retrofit alternatives to achieve satisfactory D/C ratios, a verified fiber-based analysis platform is used to assess the inelastic behavior of the existing and retrofitted buildings using inelastic pushover analysis (IPA). This step is followed by incremental dynamic analyses (IDA) using suites of earthquake records representing the seismicity of the construction site. Finally, a seismic performance index (SPI) and a performance-to-cost index (PCI) are used for prioritizing and selecting the most effective retrofit technique.

Keywords**:** Substandard Buildings, Seismic Performance, Retrofit Prioritization, Cost Considerations

1. Introduction

Although different seismic retrofit techniques for upgrading buildings were proposed in design standards and guidelines, a simple and systematic methodology for selecting the optimum retrofit measure is required [e.g., 1]. Several studies have conducted comprehensive earthquake vulnerability assessments and proposed risk-mitigation strategies that require an interdisciplinary framework encompassing hazard definition, physical damage of the exposed inventory, and socio-economic consequences [e.g., 2]. However, a systematic risk-mitigation framework needs to be put forth. Moreover, previous risk-mitigation studies have been mainly devoted to evaluating the effectiveness of specific retrofit techniques for upgrading substandard structures [e.g., 3, 4]. Fragility functions, which are the outcomes of vulnerability studies, have been adopted to estimate seismic loss and select suitable seismic retrofit techniques [5]. Nevertheless, fragility functions cannot be relied upon solely for selecting an optimum seismic retrofit solution as they do not consider cost implications. Hence, the focus of this study is to propose a systematic methodology and apply the developed framework to select an effective retrofit measure for a case study by considering the seismic performance and retrofit cost.

2. Selection of a Case Study representing Medium Seismicity Region

As a case study, the present study focuses on a medium seismicity area vulnerable to different seismic scenarios. This area is represented by Dubai, the United Arab Emirates (UAE). Various studies were directed to understand the UAE seismicity by conducting probabilistic seismic hazard assessments for the region. In this study, a design PGA of 0.16g for a 10% probability of exceedance in 50 years is adopted for the study area, following the recommendations of previous studies [e.g., 6]. The selected seismic design criteria are consistent with the UAE's currently recommended seismic design criteria. Based on the occurrence rate and spatial distribution of the earthquakes in the study region, two seismic scenarios have been recommended in previous studies for vulnerability assessment studies: (i) far-field earthquakes (M 7-8), which originate at a large epicentral distance, referred to as FF; and (ii) near-field events (M 5-6) propagating from local seismic faults, referred to as NF. In this study, eleven ground motions representing the NF seismic scenario were selected to account for the uncertainty in input ground motions and represent the latter critical seismic scenario. The mean of the response spectra of the selected eleven earthquake records matches well with the mean of twenty ground motions considered in recent seismic assessment studies for the study area [7], as shown in Fig. 1(a). Recent seismic design provisions recommend increasing the minimum number of ground motions used for response-history analyses from seven to eleven [8]. Hence, this selection of record numbers fulfills the computational workload to realistically assess the seismic performance of the existing benchmark buildings and their retrofit alternatives without compromising accuracy.

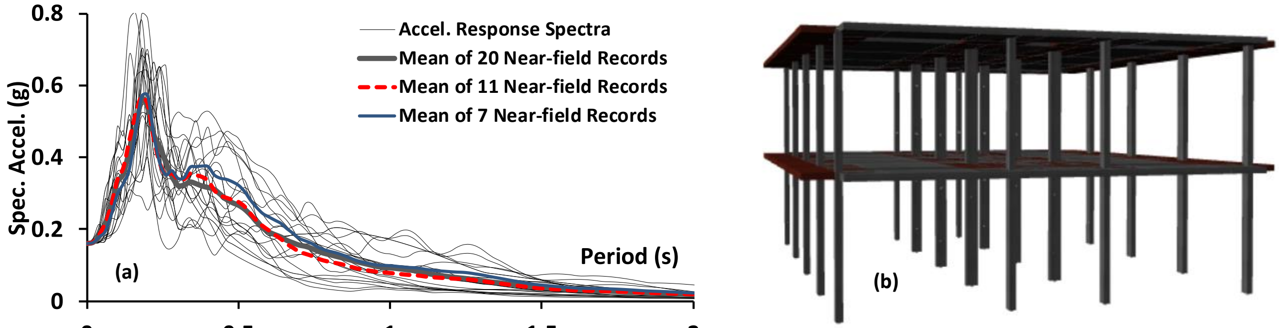

Fig. 1: (a) Response spectra of near-field (NF) earthquake records; (b) benchmark two-story MRF structure.

3. Structural System

A substandard reinforced concrete (RC) moment-resisting frame (MRF) building was selected in this study to implement retrofit techniques as they are one of the most common structural systems for the building inventory in the study region. It was designed only for gravity and wind loads in compliance with the building design provisions present at the time of construction [9]. The two-story MRF building has a total height of 8.5 m and a set of five framing systems spaced at 4.0 m in the short direction, as shown in Fig. 1(b). The floor plan of the building measures 16 m × 13 m. The ground story height is 5 m, while the first story height is 3.5 m. It is worth mentioning that, high-performance reinforced concrete (HPRC) jacketing and self-centering energy dissipative (SCED) bracing systems are the two retrofit techniques used in this study to upgrade the selected substandard RC structure.

4. Methodology for Selecting and Prioritizing Retrofit Alternatives

The systematic seismic assessment and retrofit methodology proposed and adopted in this study is depicted in Fig. 2. The procedure starts by evaluating the seismic performance of the as-built and retrofitted structures using code-prescribed analysis procedures, including Equivalent Lateral Force and Modal Response Spectrum analyses, in line with the adopted seismic design criteria (Step 1). The demand-to-capacity (D/C) ratios of critical members from flexural, axial and shear stresses under the design load combinations are investigated using 3D finite element model. Once the D/C ratios exceed unity, several effective retrofit measures are proposed to arrive at satisfactory D/C ratios (Step 2). The entire structure is then modeled using an experimentally verified fiber-based analysis platform (Step 3) to assess the inelastic behavior of the existing and retrofitted building using inelastic pushover analysis (IPA) and incremental dynamic analysis (IDA). An initial selection of promising mitigation measures through IPA is made based on the achievement of required lateral stiffness (K), overstrength factor (Ω_d) and global ductility factor (μ), (Step 4). The process returns to Step 2 for revising the retrofit alternatives if these requirements are not fulfilled. Once sufficient response parameters are fulfilled based on IPA, a further refinement of the selection is necessitated based on comparable performance, practical execution concerns and preliminary cost implications (Step 5). The effectiveness of the retrofit techniques under real earthquake records with increasing intensities is investigated by using diverse input ground motions representing the seismicity of the study region, as previously mentioned (Step 6). Furthermore, fragility functions for the existing and retrofitted structures are derived based on suitable global damage measures (GDMs) and associated performance criteria to probabilistically assess the seismic performance of the retrofit techniques (Step 7).

Calculations of damage states of benchmark and retrofitted structures are then carried out. Finally, the quantitative seismic performance index (SPI) and relative performance-to-cost index (PCI) of the selected retrofit measures relative to existing buildings are used for a final selection of the retrofit technique (Step 8).

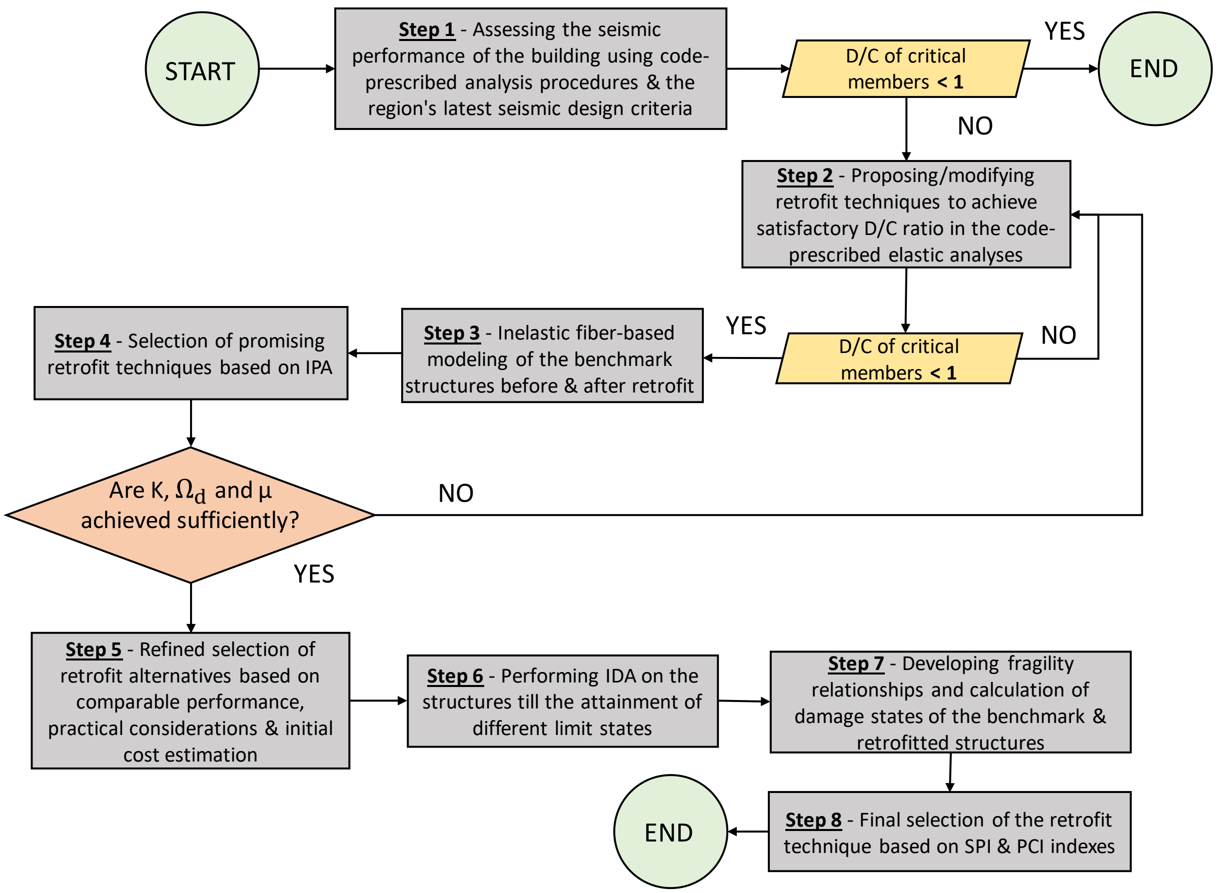

Fig. 2: Framework for the seismic assessment and prioritizing retrofit alternatives of existing buildings.

5. Ranking of Retrofit Alternatives based on Seismic Performance and Cost

As shown in Fig. 3(a), probabilistic fragility functions were derived from several inelastic multi-step dynamic response simulations performed on the substandard building and their retrofitted systems using eleven earthquake records. However, to quantify the performance of the retrofit measures from the fragility curves, a suitable SPI is needed as structural performance improvements vary for various limit states. The SPI is calculated based on the median GMI parameters of the existing structure and the retrofit alternatives at various limit states as described in a recent study [10]. However, selecting an optimum seismic retrofit solution for the benchmark structures is challenging as it is necessary to consider retrofit costs. Therefore, the cost of the adopted retrofit solutions based on the supplier and manufacturer information was estimated to arrive at PCI [10]. From Fig. 3(b), it was concluded that the SCED bracing system was the optimum seismic risk-mitigation alternative for the MRF building as this technique led to an improved seismic performance with the lowest cost.

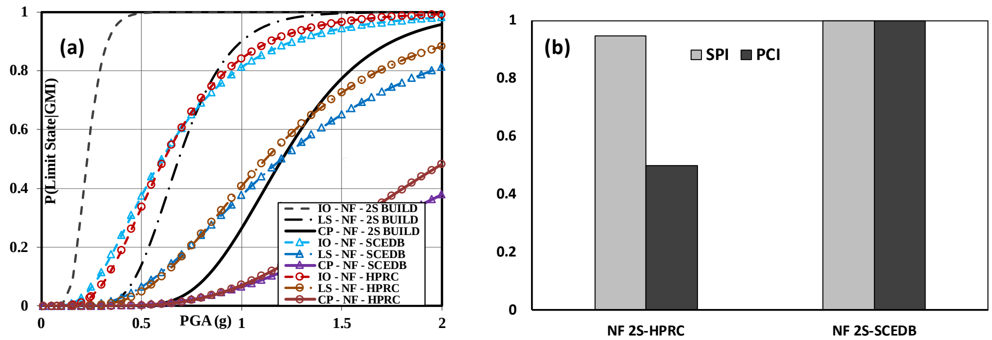

Fig. 3: (a) Fragility functions for the MRF structure and its retrofit alternatives under NF events, and (b) ranking of retrofit technique for the MRF structure based on seismic performance and cost.

6. Conclusion

This study proposed a framework for the seismic assessment and prioritization of retrofit alternatives based on their seismic performance and cost. The systematic methodology consists of several steps that can be followed to retrofit substandard structures to meet the design criteria of the region and extend into detailed seismic performance assessments involving inelastic pushover analyses (IPAs) and incremental dynamic analyses (IDAs). While this study was applied to suitably select a retrofit technique to upgrade a substandard MRF structure located in a medium seismicity region, some generality can be claimed as the framework can be applied to different structural systems and building configurations. Hence, the proposed methodology can serve as a framework in loss estimation and retrofit studies as it facilitates selecting the most effective retrofit option based on their estimated seismic loss and cost.

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