Risk Assessment of Retrofitted Steel Structures Based on FEMA P-58: a Case Study-School Buildings in Kermanshah

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ABSTRACT

Earthquake, as a common natural disaster, has always been a serious threat to human beings, cities and infrastructures. Schools are regarded as the representative of educational centers, where students spend a lot of time. Therefore, the seismic performance of such buildings should be guaranteed completely. In this study, in collaboration with the Organization for Development, Renovation, and Equipment of Schools (DRES) in Iran, a steel school building in Kermanshah city was chosen, and its seismic risk was assessed incorporating FEMA P-58 methodology in two states of before and after retrofitting process. The Lateral resisting system of the school in one direction is Eccentrically Braced Frame (EBF), and in the other direction is Concentrically Braced Frame (CBF). Due to weakness in the lateral resisting system, it was suggested that some of the braces should be replaced with stronger ones. In this study, the probability distribution of repairing time and repairing cost for different structural and non-structural components in 3 hazard levels containing 50%, 10%, and 2% in 50 years was obtained using risk analysis. The results show that in all 3 hazard levels, an increase in stiffness after retrofitting has led to a decline in the loss of drift-sensitive components and a rise in acceleration-sensitive components. Due to the dominance of the number of drift-sensitive components in this case study, the total damages and repairing time after retrofitting have negligibly decreased.

KEYWORDS

FEMA P-58 Methodology, Seismic Risk, Fragility Curves, Repair Cost, Downtime.

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1. Introduction

The 2017 Sarpol-e Zahab earthquake [1, 2] remarked the high seismicity of Iran, emphasizing the necessity of accurate seismic risk assessment of vital infrastructures, such as educational institutions. In this paper, a steel school building located in Kermanshah is investigated using the FEMA P-58 framework [3]. This approach, unlike traditional methods that mainly focus on structural response, combines structural and non-structural performance into a single risk-based assessment. Using the FEMA P-58 methodology, a probabilistic framework was employed to estimate the risk in terms of potential damage, repair costs, and downtime. The objectives are to (I) assess the building's seismic performance before and after retrofitting, (II) evaluate the effectiveness of stiffness enhancement measures, and (III) quantify expected repair costs and downtime under various seismic hazard levels.

2. Methodology

For the seismic risk analysis the FEMA P-58 methodology was adopted, which integrates probabilistic seismic hazard analysis with building-specific vulnerability data to estimate repair costs, downtime, and the probability of structural collapse. The study includes the following major components:

- The Building Model and Structural Details:

The selected school is a two-story braced-frame steel building with a rectangular plan of 14.4 m by 14.7 m. The lateral load-resisting system includes concentrically braced frames (CBF) in one direction and eccentrically braced frames (EBF) in the perpendicular direction. The original braces, consisting of small double-angle sections, did not provide adequate stiffness to meet the seismic requirements of the building. During retrofitting, selected braces in certain bays were replaced with larger double-angle sections (No. 6 upgraded to No. 8) to enhance the building's lateral stiffness and strength.

- Seismic Hazard Assessment:

Seismic hazard analysis was based on data from previous studies conducted in Kermanshah [4], accounting for local ground motion characteristics. Three hazard levels were considered: 50% probability of exceedance in 50 years (frequent, low-intensity earthquakes), 10% probability in 50 years (design-level seismic events), and 2% probability in 50 years (rare but high-magnitude earthquakes). The site-specific seismic demands were determined using Probabilistic Seismic Hazard Analysis (PSHA), yielding spectral accelerations for the building's first vibration mode under each hazard level.

- Structural Modeling and Analysis:

The building's model was developed in OpenSees [5], a finite element software for nonlinear time-history analysis. Two-dimensional models were created for both the CBF and EBF systems, capturing the inelastic behavior of the braces and their connections. Geometric nonlinearity (P-Delta effects) and material nonlinearity (steel plasticity) were included in the analysis.

- Retrofit Design and Performance Evaluation:

The goal of the retrofit was to increase the lateral force-resisting system's strength and stiffness. Particularly, braces in the EBF system were upgraded, while minor adjustments were made to the CBF system. The effectiveness of the modifications was assessed by reanalyzing the retrofitted building using the same set of earthquake ground motions.

- Damage and Loss Estimation:

Using the PACT tool from FEMA P-58, damage states for both structural and non-structural elements were determined based on the drift and acceleration demands from the IDA results. The fragility curves, specific to each building component, were used to estimate the probability of damage at different seismic intensities. These damage probabilities were then translated into expected repair costs and downtime. To perform Incremental dynamic analysis (IDA) [6] six pairs of earthquake ground motions were chosen based on the soil type and scaled to match the hazard levels. The IDA results provided key response parameters, such as inter-story drift ratios (IDR) and absolute floor acceleration, which are crucial for evaluating both structural and non-structural damage.

3. Results and discussion

In this study, the seismic risk of a steel school building in Kermanshah was assessed using the FEMA P-58 methodology in two states of before and after retrofitting. The primary lateral load-resisting systems included concentrically braced frames (CBFs) and eccentrically braced frames (EBFs). Due to the insufficient seismic capacity of these systems, retrofitting was necessary to reduce seismic vulnerabilities.

Pre-Retrofit Performance:

The EBF system had serious deficiencies prior to retrofitting, including excessive interstory drifts and the potential for collapse at the 2% in 50 years hazard level. The weakness in the EBF system capacity caused significant inter-story drifts, leading to extensive damage in structural components, as well as non-structural elements like partitions and walls. This system required immediate retrofitting due to its failure to meet seismic performance criteria, particularly at the 2% hazard level, where the risk of collapse was highest.

Post-Retrofit Performance:

Retrofitting slightly improved the performance of the building. The increase in lateral stiffness led to a reduction in the interstory drift ratios across all hazard levels. For example, at the 10% hazard level, repair costs for the building decreased from $88,250 to $82,400, representing a 6.6% reduction in expected losses. The cumulative distribution function (CDF) of the total repair cost of the building at all three hazard levels is shown in Fig. 1, illustrating the leftward shift of all curves after the retrofitting process.

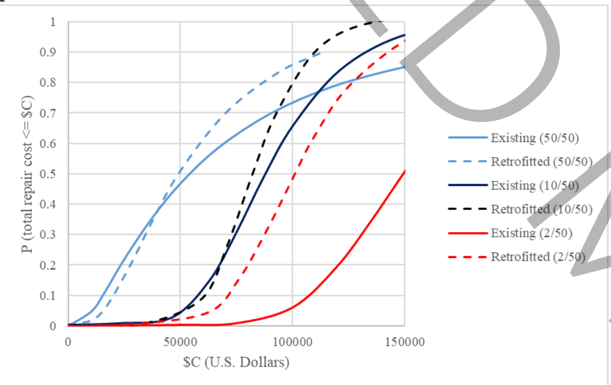

Fig. 1. Cumulative Probability Distribution Curves of Total Repair Costs for Existing and Retrofitted Structures at Three Seismic Hazard Levels.

However, retrofitting also caused an increase in acceleration-induced damage. Acceleration-sensitive components, such as suspended ceilings, were damaged more due to the increased accelerations that resulted from retrofitting, particularly at high seismic hazard levels. Despite this, the overall repair costs were moderately reduced across all hazard levels due to the dominance of the number of drift-sensitive members. In terms of downtime, the probabilistic seismic risk analysis showed a reduction in the total repair time after retrofitting. For example, at the 50% hazard level, repair time decreased from 122 days to 112 days in the serial repair model. Likewise, the retrofitted structure showed improved performance with marginally less downtime at the 10% and 2% hazard levels. The parallel repair model exhibited even greater reductions in repair time, especially at the 2% hazard level, where downtime decreased from 365 days to 141 days after retrofitting.

Comparative Analysis of Hazard Levels:

The results demonstrate that the benefits of retrofitting are more pronounced at the highest hazard level. For the 50% and 10% hazard levels, the reduction in repair costs was approximately 8% and 6%, respectively, while at the 2% hazard level, the reduction was about 32% due to the prevention of total collapse.

4. Conclusions

This study illustrates the efficacy of the FEMA P-58 methodology in evaluating the seismic risk of an existing steel school building before and after retrofitting. The probabilistic nature of the assessment provides a robust framework for estimating repair costs and downtime, which are critical factors for stakeholders when deciding on retrofitting strategies. The retrofitting measures implemented in this study slightly reduced the building's vulnerability to drift-induced damage, though some acceleration-sensitive components remained at risk. The findings suggest that while retrofitting improves overall building resilience, further optimization is required to minimize the impacts on acceleration-sensitive components. Future work should explore alternative retrofitting solutions that balance stiffness and flexibility, reducing both drift and acceleration demands.

5. References

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