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SEISMIC PERFORMANCE EVALUATION OF EXISTING REINFORCED CONCRETE BUILDINGS IN SKOPJE

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Abstract

The vulnerability of the built environment to seismic events has been increasingly evident, particularly in the Balkan region, where recent earthquakes have caused significant non-structural damage to both old and new buildings, often leading to restricted use. In North Macedonia, seismic design standards were introduced only after the catastrophic Skopje earthquake in 1963, with the first seismic code implemented in 1964. The construction of reinforced concrete buildings, which began at that time and continues even today, are now regarded as unique monuments of that era. These structures are a significant part of the urban landscape and reflect the evolution of engineering practices in the region. In recent years, there has been a focus on improving building features such as energy efficiency and facade renovations, but seismic evaluation and retrofitting have not been prioritized, as they are not required by national regulations.

This gap highlights the urgent need for guidelines to evaluate the seismic performance of existing buildings, allowing for the estimation of both direct and indirect losses associated with restoring building functionality, as well as the identification of key parameters influencing these losses. To address this, the economic loss prediction method outlined in FEMA-P58 is applied to residential buildings in Skopje's city center, which were constructed after the 1963 earthquake. These buildings serve as prototypes for assessing seismic performance using a scenario-based approach. The findings provide insights into expected repair costs due to earthquake-induced damage. Ultimately, the results of this study contribute to the establishment of performance-based objectives and procedures for assessing the recovery of existing buildings, providing valuable insights for future seismic resilience strategies and building safety improvements.

Keywords: FEMA P-58 methodology, performance-based seismic design, reinforced concrete frame buildings, vulnerability assessment, repair cost estimation, existing building stock.

1. Introduction

The seismic resilience of existing reinforced concrete buildings remains a critical concern, particularly in seismically active regions such as North Macedonia. The devastating 1963 Skopje earthquake marked a turning point in the country's construction practices, leading to the development of the first seismic design codes. [12] Despite the subsequent improvements, many buildings constructed during this transitional period remain vulnerable to seismic events due to their adherence to early code provisions. The need for robust assessment methodologies that can evaluate both direct and indirect earthquake-induced losses has thus become increasingly evident. [10]

To address this challenge, this study proposes an integrated approach combining the established methodology developed at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) [7] with the FEMA P-58 framework [3]. The IZIIS methodology, widely applied in the region,

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incorporates detailed assessments of the structural system, mainly based on local regulatory requirements. However, it lacks a systematic probabilistic approach for damage and loss estimation analysis. On the other hand, FEMA P-58 provides a performance-based framework that quantifies repair costs, downtime, and safety risks using probabilistic models [5]. By integrating these methodologies, the proposed approach leverages the strengths of both: the contextual specificity of the IZIIS methodology and the systematic loss estimation capabilities of FEMA P-58.

The definition of seismic hazard in this study relies on site-specific investigations of local soil conditions. These investigations provide critical input for developing accurate acceleration response spectra, ensuring that the seismic hazard characterization reflects the unique geotechnical and seismological conditions of the studied locations.

An essential aspect of this integration is the development of fragility curves for structural and non-structural components, as well as loss functions tailored to the local context and the period of construction. These fragility curves and loss functions capture the unique characteristics of Macedonian buildings constructed during the era following the 1963 Skopje earthquake, enabling a more precise evaluation of their seismic vulnerability and potential losses.

This paper applies the integrated methodology to moment resisting reinforced concrete buildings within the "Gradski Zid" complex in Skopje, a representative case study of structures built shortly after the 1963 earthquake. These buildings serve as prototypes for demonstrating the practical application of the integrated approach. The integration allows for a comprehensive evaluation of seismic performance, considering not only immediate structural responses but also basic recovery needs and costs. The findings contribute to advancing performance-based design practices and enhancing resilience strategies tailored to the unique characteristics of Macedonian building stock.

By bridging the gap between local methodologies and international standards, this study aims to provide a robust framework for assessing and improving the seismic resilience of existing buildings in North Macedonia, addressing critical gaps in current reconstruction practices and laying the groundwork for future research in the field.

2. Assessment of the Behavior of Existing Reinforced Concrete Frame Buildings Using the FEMA P-58 Methodology

The previously discussed methodology was applied to existing reinforced concrete buildings constructed during the period between the adoption of the first seismic design standards (1964) and the adoption of the current standards in 1981, in North Macedonia. This period is considered a time of robust construction practices, characterized by structural design carried out by experienced engineers, strict supervision, quality control of construction materials, and mandatory inspection and testing [12].

For prototype buildings, residential structures from the "Gradski Zid" complex in the center of Skopje were selected. These buildings, constructed after the 1963 Skopje earthquake, include a substantial number of structures representative of the buildings of interest. The analysis utilized the integrated approach of combining site-specific seismic hazard characterization with fragility curves and loss functions tailored to the local context and the specific period of construction. To conduct analyses of the prototype buildings, the following input data were prepared:

- Seismic hazard characterization: Developed based on site-specific investigations of local soil conditions, providing critical input for accurate acceleration response spectra. [6]
- Fragility functions and consequence models: Extensive experimental data collected from the database of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), as well as experimental studies conducted in other European countries, were used to establish these for structural and non-structural components of the buildings.
- Technical documentation and building information: Review of available technical documentation for the buildings and additional required information from building owners were used to develop detailed performance models of the buildings. [13]

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This combination of methodologies ensures a comprehensive evaluation of the seismic behavior of the selected structures, accounting for both immediate structural responses and potential economic losses due to damage, repair costs, and recovery timelines.

2.1. Selection of Ground Motion Time Histories

In accordance with the prescribed methodology defined in FEMA P-58, the seismic excitation is characterized using a target acceleration response spectrum tailored specifically for the studied location. For this site, the seismic potential was rigorously evaluated through detailed site-specific investigations of local soil conditions, ensuring that the acceleration spectrum accurately reflects the unique geotechnical and seismological characteristics of the area [6].

Based on the disaggregation of seismic hazard, two distinct hazard levels were considered.

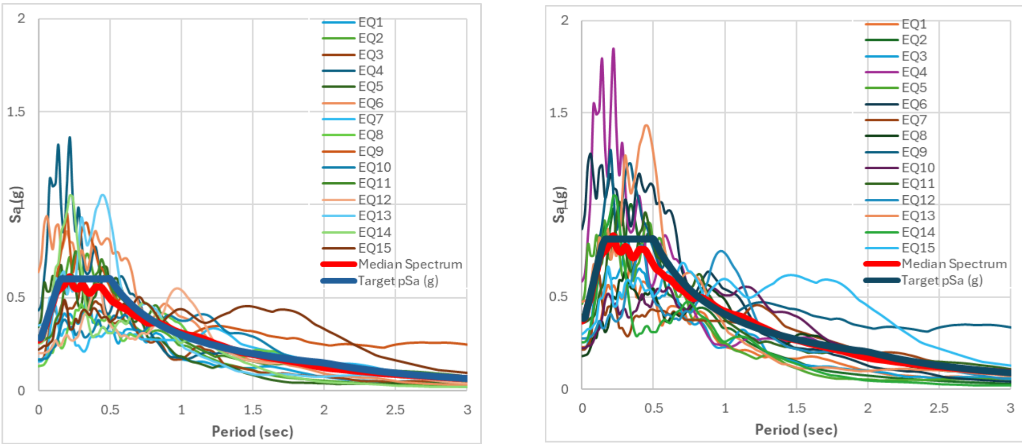

Figure 1. Appropriately selected earthquake spectra according to the considered hazard levels: Design Level Earthquake (DL) – left, Maximum Level Earthquake (ML) – right

The earthquake levels are associated with return periods of 475 and 950 years, referred to as the Design Level (DL) and Maximum Level (ML), respectively. For each level, 15 pairs of ground motion records were selected with spectra matching the target response spectrum for the specific location. Figure 1 illustrates the response spectra of the selected ground motion histories alongside the target response spectrum for the studied location.

2.2. Building Performance Model

The building performance model incorporates several key input parameters: (i) basic data about the building, (ii) data on vulnerable structural and non-structural components, (iii) structural analysis data, (iv) potential residual deformation data, (v) data on the probability of collapse, and (vi) the expected seismic hazard at the building's location.

The basic building data includes the size and geometry of the structure, the total replacement cost, and a loss threshold, which defines the conditions under which repairing the building is deemed uneconomical, prompting a replacement instead.

Vulnerable structural and non-structural components are defined by specific fragility curves and the quantity of components within each performance group. Table 1 presents the considered vulnerable components included in the analysis.

To determine the number of realizations required, preliminary analyses were conducted, varying the number between 100 and 2500. The results indicated minor increases in loss estimates between 100 and 2000 realizations, while increases from 2000 to 2500 were negligible. Consequently, 2000 realizations were adopted. Each realization represents a unique set of simulated building responses, including inter-story drift ratios (IDRs), peak floor accelerations (PFAs), and residual drift ratios.

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Each realization was generated in the "PACT" software using a Monte Carlo simulation process, based on results from a nonlinear response history analysis and the selected dispersion of the model (βm). The dispersion (βm) was calculated as the square root of the sum of the squares of two sources of uncertainty: one related to the definition level of the building and construction quality (βc), and the other associated with the quality and comprehensiveness of the nonlinear structural analysis model (βq). In this study, the values of βc and βq were 0.4 and 0.25, respectively, in accordance with FEMA P-58 recommendations.

Table 1. Fragility Components and Required Parameters

Fragility Components	Demand Parameter
External joints_EWJ	Inter-story drift (%)
Internal joints_IWB	Inter-story drift (%)
Weak foundation columns_DWC	Inter-story drift (%)
Slender columns_BWC	Inter-story drift (%)
Exterior walls without openings	Inter-story drift (%)
Exterior walls with openings	Inter-story drift (%)
Partition walls without openings	Inter-story drift (%)
Partition walls with openings	Inter-story drift (%)
RC stairs with rigid joints	Inter-story drift (%)
Elevator	Floor acceleration (g)

2.3. Case Study Building: “Gradski Zid” Tower

The case study building is a 14-story residential structure located in the center of Skopje, North Macedonia. The building was designed and constructed with a reinforced concrete (RC) frame structural system. The analytical model of the structure is shown in Figure 2 - left, while the layout plan illustrates its symmetrical design along both orthogonal axes (Figure 2, right).

The total floor area is approximately 5830 m², with an average floor area of 370 m². All values for the dimensions of structural elements and material properties were adopted based on the available documentation (Table 2). [13]

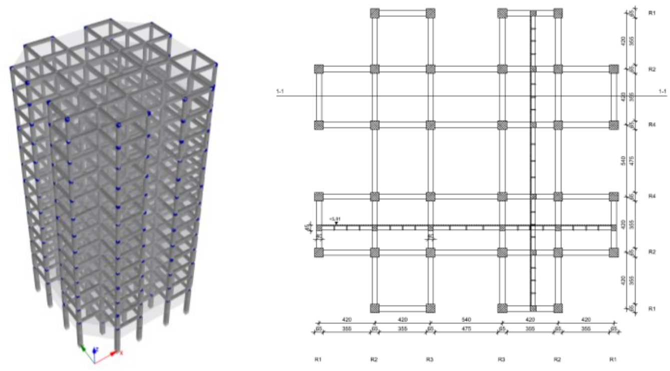

Figure 2. View of the analytical model (left) and the characteristic floor plan (right).

Table 2. Dimensions of Elements and Material Properties

Structural Features	Specifications
Column dimensions [cm]	65/65, 60/60, 55/55, 50/50, 45/45, 40/40
Beam dimensions [cm]	60/65, 65/50, 50/50, 40/45
Floor system	Ribbed slab (rib height 40 cm, slab thickness 8 cm)
Concrete and reinforcement	fc = 30 MPa, GA240/360

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2.4. Description of the Analytical Model

The analytical model for the prototype structures was developed using the SeismoStruct software [9]. The model includes reinforced concrete (RC) structural elements such as columns and beams, while the floor slabs were simulated as diaphragms with constraints at the floor levels. Based on observations of damage manifested during past earthquakes in buildings constructed during the same period, the nonlinear behavior of joints, identified as the weakest points of the structural elements, was incorporated into the model.

The nonlinear behavior of internal joints was simulated using plastic hinges at the ends of the elements, with non-elastic behavior defined according to the designed cross-sectional characteristics of the original construction project. The nonlinear behavior of external joints was modeled using the “Scissors model” [8], which combines beam-column elements and spring connections at the joints. The joint region is represented by a series of rigid links with a central rotational spring to account for shear deformation in the joint region.

Gravitational loads were assigned based on architectural drawings from the available documentation and materials commonly used during the construction period. Live loads were estimated following FEMA P-58 guidelines, as 25% of the designed expected loads [3].

2.5. Results of Nonlinear Time History Analysis

The previously described analytical model was subjected to analysis using two sets of 15 earthquake ground motion records each. Each set corresponds to a specific hazard level: a return period of 475 years, referred to as the Design Level (DL), and a return period of 950 years, referred to as the Maximum Level (ML). For further analysis results for inter-story drift, floor accelerations, residual drift and collapse occurrence are used. The analysis results for inter-story drift and peak floor accelerations along the x and y directions are presented in Figures 3 and 4.

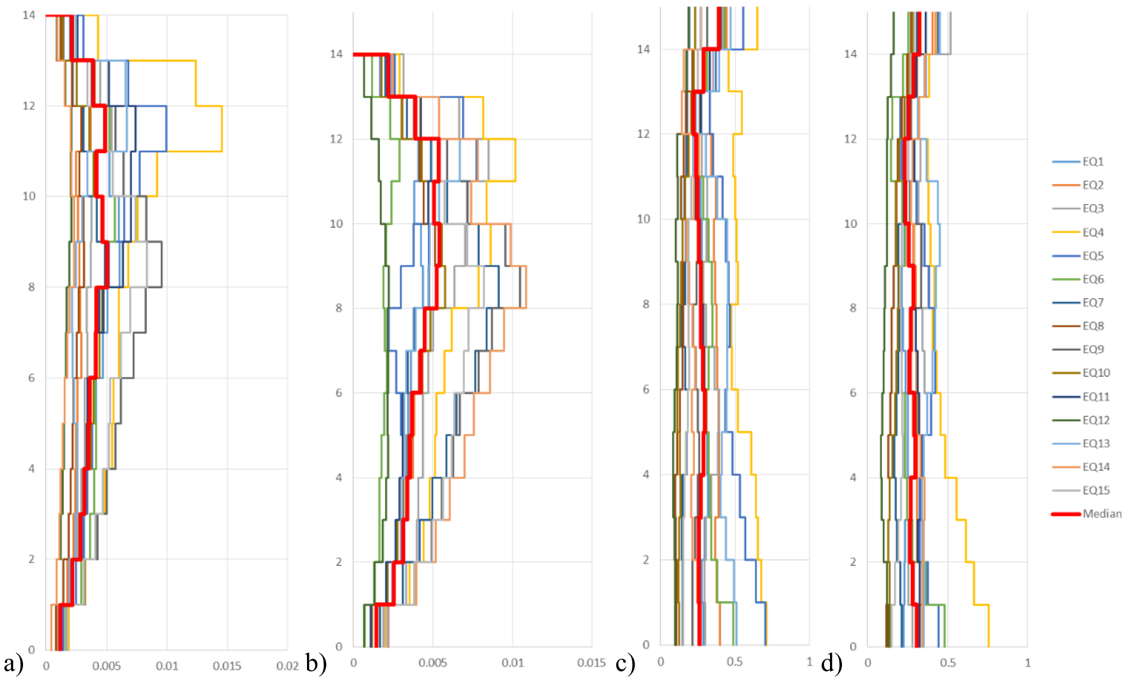

Figure 3. Inter-story drifts (a,b) and peak floor accelerations (c,d) for the x and y directions at the Design Level earthquake.

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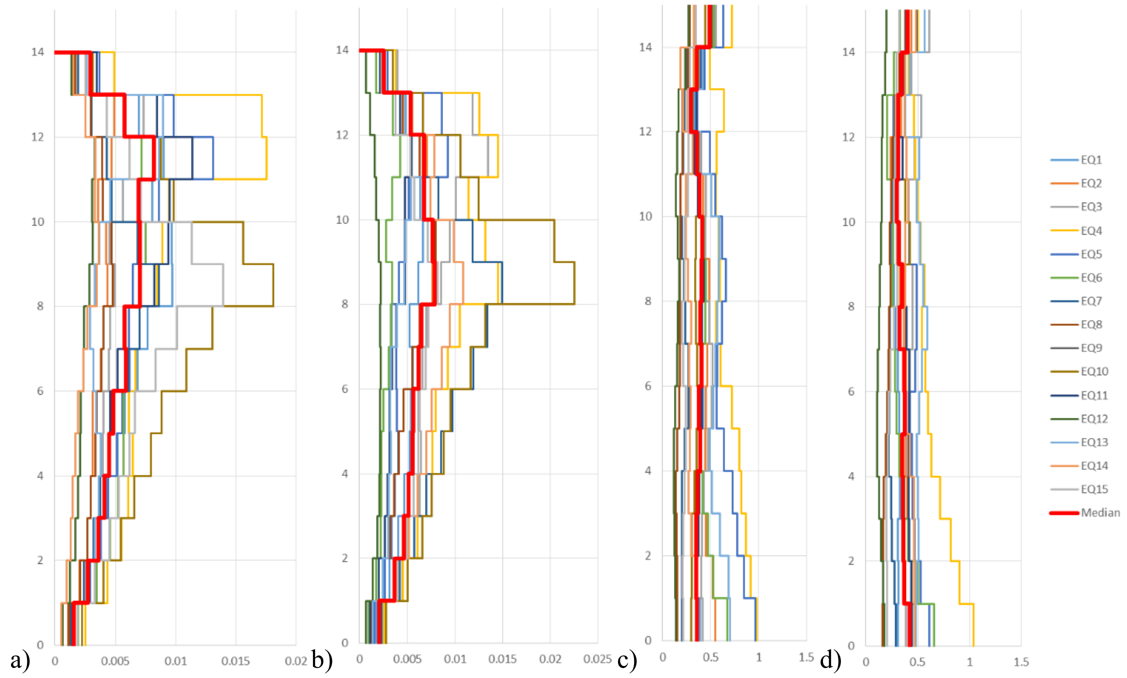

Figure 4. Inter-story drifts (a,b) and peak floor accelerations (c,d) for the x and y directions at the Maximum Level earthquake.

2.6. Results of the Seismic Scenario-Based Assessment of Building Behavior

For the previously defined hazard levels, analyses were performed based on two scenarios. The results are expressed as estimates of potential losses or costs associated with building repairs. In generating these scenarios, the total economic loss was assumed to be equivalent to the replacement cost of the building. The results obtained from the nonlinear analyses determined the economic loss for each defined vulnerable component of the building, correlating with the corresponding fragility functions (Table 2).

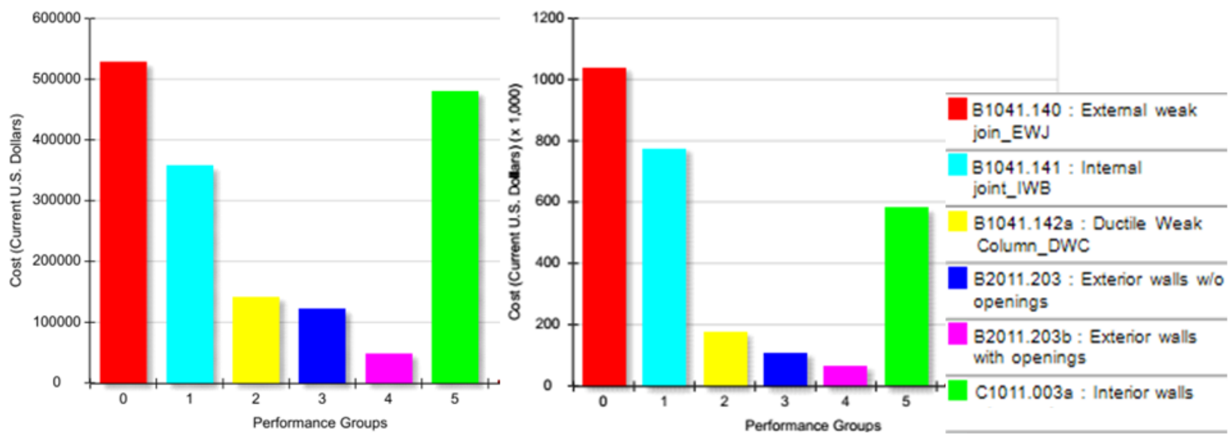

Figure 5. Repair costs distributed by fragility groups: Design Level earthquake (left) and Maximum Level earthquake (right).

Figure 5 illustrates the repair costs derived from 2000 realizations for the evaluated hazard levels and scenarios. For the 475-year return period, designated as the Design Level (DL), and the 950-year return period, designated as the Maximum Level (ML), repair costs are ordered by magnitude and broken down into contributions from each vulnerability group. The results indicate that structural components contribute the most to the building's losses, as repair costs for these components are the highest.

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However, the costs of repairing damage to non-structural elements, such as masonry infills, are also significant.

The expected loss for each scenario represents the anticipated repair cost under a specific seismic intensity scenario. The results reveal a median repair cost of $1,683,545 for the DL scenario and $2,780,618 for the ML scenario.

The repair costs were normalized relative to the replacement cost of the building. Table 3 presents the normalized repair costs in relation to the total replacement cost.

Table 3. Normalized Repair Costs for the Building

Scenario	**Replacement Cost [$]**	**Expected Loss [$]**	**Loss-to-Replacement Cost Ratio [%]**	**Repair Cost per m² [$]**
DL	4 265 272	1 683 545	39.4%	312.46
ML		2 780 617	65.2%	516.07

Considering the data provided by FEMA P-58 on the expected repair time for potential damage, it becomes evident that the repair timeframe would also be significant. Figure 6 presents the time required for repairs if all floors are repaired simultaneously. However, this type does not provide an accurate picture of the actual repair timeline.

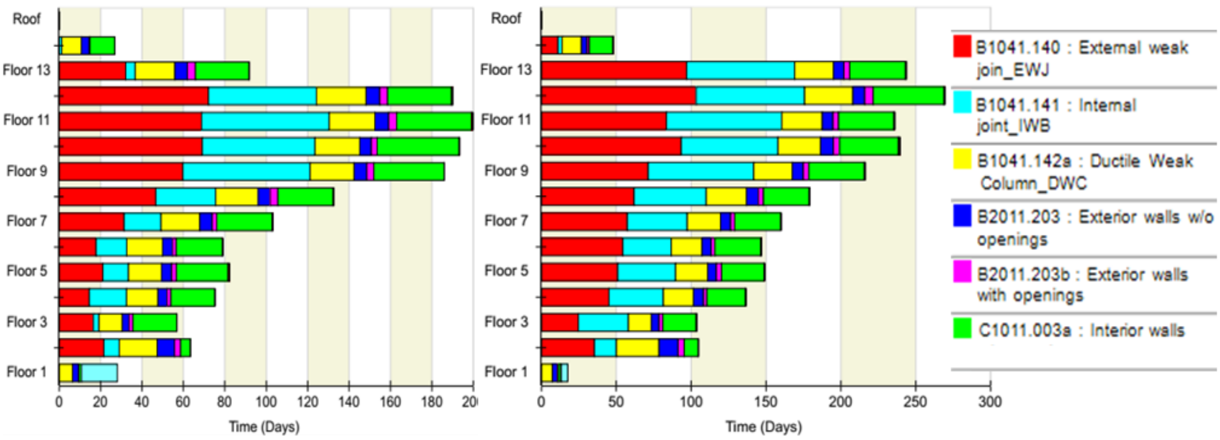

Figure 6. Repair time per floor: Design Level earthquake (left) and Maximum Level earthquake (right).

Certain limitations exist with this method of calculating repair time. The input parameters used in this methodology do not account for flexible allocation of labor, appropriate scheduling of work, and similar factors [14]. To accurately estimate the repair timeline, additional analyses are required to consider a broader range of factors, such as workforce availability and the organization of the repair process. These aspects will be addressed in future research.

3. Conclusions

The integration of the IZIIS methodology with the FEMA P-58 framework represents a significant advancement in the seismic assessment of existing reinforced concrete buildings in North Macedonia. By combining site-specific seismic hazard characterization with fragility curves and loss functions tailored to the local context and construction period, this approach addresses critical gaps in conventional assessment methodologies. The localized investigations, particularly those capturing unique soil characteristics, provide a robust foundation for precise hazard definition and response spectra.

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The application of this integrated methodology to the "Gradski Zid" complex in Skopje demonstrates its practical utility in assessing the vulnerability and recovery potential of buildings constructed after the 1963 Skopje earthquake. The findings underscore the importance of tailoring international frameworks to regional contexts to enhance accuracy in predicting damage, repair costs, and recovery timelines. This integration offers a comprehensive evaluation, bridging immediate structural responses with long-term resilience planning.

This study provides a framework that can guide policymakers and engineers in developing seismic retrofitting strategies and resilience planning specific to the Balkan region. Moreover, it sets a precedent for adapting performance-based methodologies to local conditions, offering valuable insights for other seismically active regions worldwide.

Future research should focus on refining fragility functions and consequence models for non-structural components, as well as improving repair timeline estimations by integrating logistical and resource allocation considerations. Additionally, expanding the application of this methodology to other building typologies and regions within North Macedonia will enhance its generalizability and practical relevance.

By advancing a performance-based approach tailored to the unique characteristics of Macedonian building stock, this study contributes to the global discourse on seismic resilience, highlighting the importance of localized adaptations to international frameworks for improved safety and functionality of the built environment.

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