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SEISMIC ASSESSMENT AND COST-BENEFIT ANALYSIS OF RETROFITTING MEASURES FOR POST-WAR MULTI-RESIDENTIAL MASONRY BUILDINGS IN LJUBLJANA

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Abstract

This study presents an integrated approach to seismic assessment and retrofitting of multi-residential masonry buildings constructed between 1945 and 1963 in Ljubljana, Slovenia. These buildings, characterized by unreinforced masonry walls and prefabricated floor slabs, represent a significant portion of the urban housing stock and are highly vulnerable to seismic loading.

The paper develops a standardized typology classification based on building shape, number of stories, and number of cores, identifying over 400 buildings across Ljubljana. Four representative building types were selected for detailed seismic performance assessment using the equivalent frame approach in 3Muri software. Two retrofitting scenarios using Fibre Reinforced Cementitious Matrix (FRCM) systems were evaluated: selective strengthening of critical elements and comprehensive strengthening of all load-bearing walls.

Results show that while FRCM retrofitting improves seismic performance, most retrofitted configurations fail to fully meet Eurocode 8 requirements. Cost-benefit analysis reveals that selective retrofitting requires 5-8% of property value investment, while comprehensive strengthening demands 17-23%, suggesting that additional strengthening measures may be necessary despite economic considerations.

The research provides critical insights for developing economically viable seismic risk mitigation strategies that balance structural safety requirements with financial constraints. This approach offers valuable guidance for addressing similar challenges in seismic-prone regions with comparable post-war building stocks.

Keywords: Seismic vulnerability assessment, Unreinforced masonry buildings, Post-war residential architecture, Building typology classification, Nonlinear static analysis, Seismic retrofitting, FRCM strengthening, Cost-benefit analysis.

1. Introduction

Multi-residential masonry buildings constructed between 1945 and 1963 in urban centres across former Yugoslavia represent a significant portion of the housing stock and are highly vulnerable to seismic loading [1], [2], [3], which became very clear after the 1963 Skopje earthquake [4]. These buildings, characterized by unreinforced masonry walls and prefabricated floor slabs, require a comprehensive approach to seismic vulnerability assessment and retrofitting measure planning.

Existing research indicates that these buildings often fail to meet modern seismic safety requirements. This is particularly concerning in cities with high seismic hazard, such as Ljubljana, where these buildings constitute a substantial portion of the multi-residential housing stock. Although many buildings have undergone energy efficiency renovations, most have not received structural reinforcement to improve their seismic resistance.

This study develops a standardized typology classification and conducts detailed seismic performance assessments using the equivalent frame approach. The research focuses on four representative building types from Ljubljana, which are analysed using 3Muri software – a commercial version of TREMURI, originally developed by Lagomarsino and co-authors [5]. Special attention is given to evaluating the

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effectiveness of various retrofitting strategies, particularly Fibre Reinforced Cementitious Matrix (FRCM) systems, both in terms of structural improvement and economic feasibility.

The study also incorporates cost estimations for retrofitting measures based on current market prices and compares these to potential property value increases and avoided seismic losses. This cost-benefit analysis considers both structural safety and architectural preservation, as these buildings often represent an important part of cities' cultural identity.

The results of this research will provide valuable insights for policymakers and stakeholders involved in urban renewal and seismic risk mitigation across the former Yugoslavia region. The research contributes to developing sustainable strategies for enhancing urban resilience against seismic hazards, balancing safety, economic considerations, and architectural preservation. This approach offers valuable guidance for addressing similar challenges in seismic-prone regions with comparable post-war building stocks.

2. Building Identification and Typological Classification

2.1. Post-war Residential Neighbourhoods

In the first two decades following World War II, Slovenia experienced significant socio-economic changes and accelerated industrialization, leading to increased migration from rural areas to cities [6]. Additionally, there was substantial immigration from other Yugoslav republics to major Slovenian cities. This created an intense housing shortage, prompting large-scale construction of multi-residential buildings to address the urgent need for housing.

The first large multi-residential neighbourhoods began to appear in Ljubljana and other major Slovenian cities, following modernist architectural patterns. These neighbourhoods were characterized by their functional design, standardized construction methods, and community-oriented planning. Two pioneer neighbourhoods in Ljubljana, "Litostrojsko naselje" [7] and "Savsko naselje" [9], stand out as early examples of post-war modernist development.

Figure 1: Aerial photograph of "Litostrojsko naselje".

These buildings were typically constructed using traditional techniques in the earlier period, later incorporating prefabricated elements. The buildings are predominantly low- to medium-rise with flat or gently sloped roofs, adhering to modernist principles of simplicity and practicality. Their facades are

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characterized by rhythmic window arrangements, often complemented by balconies or loggias, contributing to the cohesive and utilitarian aesthetic of Ljubljana's post-war urban landscape.

The vertical load-bearing structure typically consisted of unreinforced masonry walls, with varying materials and mortar types used at different levels. The ground and intermediate floors often utilized solid clay brick masonry with lime-cement mortar for added strength, while hollow clay bricks were occasionally employed. Floor structures were commonly constructed using semi-prefabricated systems, consisting of reinforced concrete joists alternated with hollow clay elements, topped by a thin reinforced concrete compressive slab.

It is worth noting that the construction quality in these post-war residential developments varied significantly. The rapid pace of construction and the large-scale nature of these developments, coupled with material shortages and the need for quick housing solutions, often led to compromises. The construction process frequently involved local residents, which, while fostering a sense of community ownership, meant that not all workers had professional construction experience, potentially affecting the overall quality and consistency of the buildings.

Today, these neighbourhoods represent a significant portion of Ljubljana's housing stock, with many buildings requiring both energy efficiency improvements and seismic retrofitting. Understanding their architectural and structural characteristics is crucial for developing appropriate intervention strategies that respect both their historical significance and the need for modern safety standards.

2.2. Criteria and Parameters for Typological Classification

To identify suitable buildings for our study, we utilized publicly accessible spatial information system databases within the City Municipality of Ljubljana (MOL). The collected data was processed using a commercial GIS software package, focusing on MOL due to the extensive available data. The selection criteria given in Table 1 were considered.

Table 1. Selection criteria for identification of buildings.

Selection Criteria	Parameter Range
Construction period	1945-1963
Number of stories	3-7 above-ground floors
Number of apartments	≥ 9 units

This selection process identified over 400 structures that met these criteria, distributed across various clusters in Ljubljana. The identified buildings were then categorized into distinct typologies based on their geometric and structural characteristics. For each identified typological class, we gathered data on architectural features, load-bearing structure design, materials used, and construction details from original project documentation in various archive records [9]. Complete data was obtained for 62 buildings, including original architectural plans and technical reports. This detailed information allowed for accurate characterization of each building type's structural system and potential seismic vulnerabilities.

A naming convention is used, where the first segment (S, R, CS, or CR) describes the building's shape, the second segment indicates the number of above-ground floors, and the last segment indicates the number of entrances that indicate individual building cores. The shape of the building is further divided into three groups:

- **S**: Square or nearly square buildings with a length-to-width ratio between 1.0 and 1.2.
- **R**: Rectangular buildings with a length-to-width ratio greater than 1.2 or less than 1.0.
- **CS/CR**: Compound shape formed by combining two identical S-shape buildings (CS) or compound shape formed by combining one S-shape and one R-shape building (CR).

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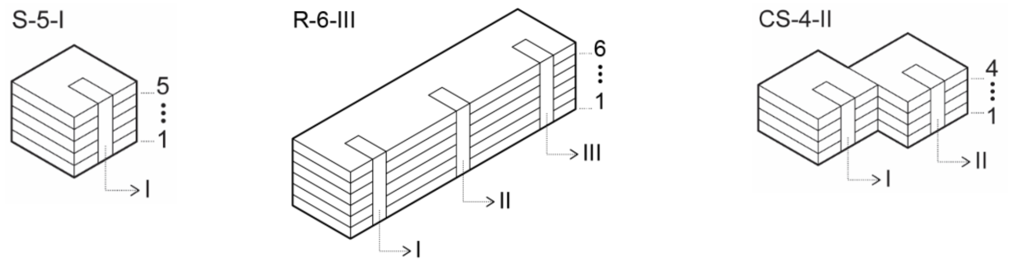

Figure 2: Schematic typology representation.

The classification coding system combines these parameters. For example, "R-4-II" represents a rectangular-shaped building with 4 stories and 2 communication cores. This standardized approach enables systematic analysis of similar building types.

The classification methodology proved particularly valuable for seismic vulnerability assessment as it groups buildings with similar structural characteristics and expected seismic behaviour. This approach allows for estimating the seismic vulnerability of a large number of buildings without performing detailed individual evaluations, which would be costly and time-consuming. Furthermore, it helps identify the most common and critical building types in the region, facilitating the prioritization of seismic retrofitting interventions.

Significant variations were observed across the typological classes in terms of:

- floor plan dimensions and configurations,
- wall-to-floor area ratios,
- structural system arrangements,
- construction materials and techniques,
- building height and slenderness ratios.

This classification system provides a framework for developing targeted seismic assessment and retrofitting strategies appropriate for each building type, considering their specific structural characteristics and vulnerabilities.

3. Seismic Performance Assessment and Retrofitting Strategies

3.1. Numerical Modelling and Performance Assessment

To evaluate the seismic performance of typical post-war masonry buildings in Ljubljana, four representative building prototypes were selected based on their prevalence and geometric characteristics. As shown in Figure 3, Building S (S-5-I) represents a compact, nearly square five-story structure measuring 16.6 x 14.8 meters, with a centralized communication core and symmetrically distributed apartments. It exhibits notably different wall ratios in its principal directions, with 6.5% in the longitudinal direction versus 2.9% in the transversal direction. Building R (R-6-III) presents a contrasting configuration as a six-story rectangular building spanning 62.8 meters in length, featuring three communication cores. Its elongated form results in reversed wall ratios compared to Building S, with 2.8% longitudinal and 6.5% transversal, reflecting its distinct structural arrangement.

The compound-shaped buildings, CS (CS-4-II) and CR (CR-6-III), represent more complex geometric configurations. Building CS combines two four-story square structures arranged in an L-shape, with dimensions of 15.6 x 13.5 meters and two communication cores. It maintains relatively balanced wall ratios of 6.1% longitudinal and 4.1% transversal, reflected in its similar fundamental periods of vibration (0.40s and 0.48s respectively). Building CR, a six-story structure combining rectangular and square forms over a 32.6-meter length, features three communication cores and demonstrates more balanced structural characteristics with wall ratios of 5.5% longitudinal and 6.4% transversal. As depicted in the floor plans and 3D representations in Figure 3, these four prototypes encompass key

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variations in shape, height, and structural configuration found across Ljubljana's post-war residential buildings, providing a comprehensive basis for seismic assessment while representing distinct approaches to multi-residential construction of that era.

The seismic performance of these four representative building typologies was evaluated using nonlinear static (pushover) analyses in the 3Muri software. For this analysis it was crucial to define the longitudinal and transverse direction since there is quite a difference between the percentage of the walls, between the two directions, in some building prototypes, which greatly impacts the results. As seen in Figure 3 we defined the longitudinal direction as the axis aligned with the longer side of the building or the main entrance. The 3Muri software employs an equivalent frame modelling approach, where masonry walls are represented as piers, spandrels, and rigid nodes, allowing for an efficient assessment of buildings' capacity to resist seismic actions considering material nonlinearity. Similar modelling approaches using the 3Muri software have been successfully applied in previous studies to analyse historical unreinforced masonry buildings, such as those damaged during the 2020 Zagreb earthquake [11]. The analysis generated capacity curves which were compared with inelastic response spectra using the N2 method. Each building's response was analysed in both longitudinal and transversal direction to assess their vulnerabilities and identify potential retrofitting needs.

3.2. Numerical Modelling and Performance Assessment

Each prototype was analysed in three structural states to capture the impact of retrofitting measures. Beside the first state, which represents the original unreinforced masonry (URM), characterized by the vulnerabilities inherent in historic masonry structures, two additional retrofitting scenarios were developed to evaluate the effectiveness of different strengthening strategies, the position of the application of FRCM for these scenarios, can be seen on Figure 4. The first scenario, Selective Retrofitting (RET), focused on reinforcing critical structural elements. These included the building cores (BC), which are the central stairwells essential for overall stability, the outer piers (OP), which are vertical elements on the external walls that experience significant vertical force variation, and the outer walls (OW) in the Y-direction, which provide additional lateral stability.

The second scenario, All Walls Retrofitting (RET-AW), involved a more comprehensive application of FRCM to all load-bearing walls throughout the structure. This approach encompassed not only the elements included in the RET scenario—building cores, outer piers, and outer walls—but also internal vertical elements in the X-direction, referred to as inner piers (IP), and internal walls in the Y-direction, known as inner walls (IW). This strategy aimed to achieve uniform strengthening across the entire structure. These retrofitting configurations were tailored to each building's structural characteristics. For example, Building R's elongated shape and numerous openings necessitated a larger increase in retrofitted wall area under the RET-AW scenario compared to RET. Conversely, Building S saw significant increases in both directions with RET-AW, effectively doubling the strengthened area longitudinally.

The study followed guidelines from CNR-DT 215/2018 [12], using alkali-resistant (AR) glass fibres for FRCM reinforcement. AR glass fibres were selected for their durability in alkaline environments and strong mechanical properties. The FRCM was applied symmetrically on both sides of masonry elements, covering piers, walls, and spandrels in a bi-directional configuration. This approach not only increased in-plane capacity but also enhanced crack control and system integrity, particularly after cracking onset. Preliminary analysis showed that both longitudinal (X-direction) and transverse (Y-direction) strengthening were necessary for the studied buildings [9], [13]. Both retrofitting approaches were complemented by the installation of horizontal steel ties around the building perimeter at each floor level. These ties enhanced the structure's box-like behaviour, reducing the risk of out-of-plane

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wall failure during seismic events. By improving load distribution, the ties bolstered the overall effectiveness of FRCM strengthening in both scenarios.

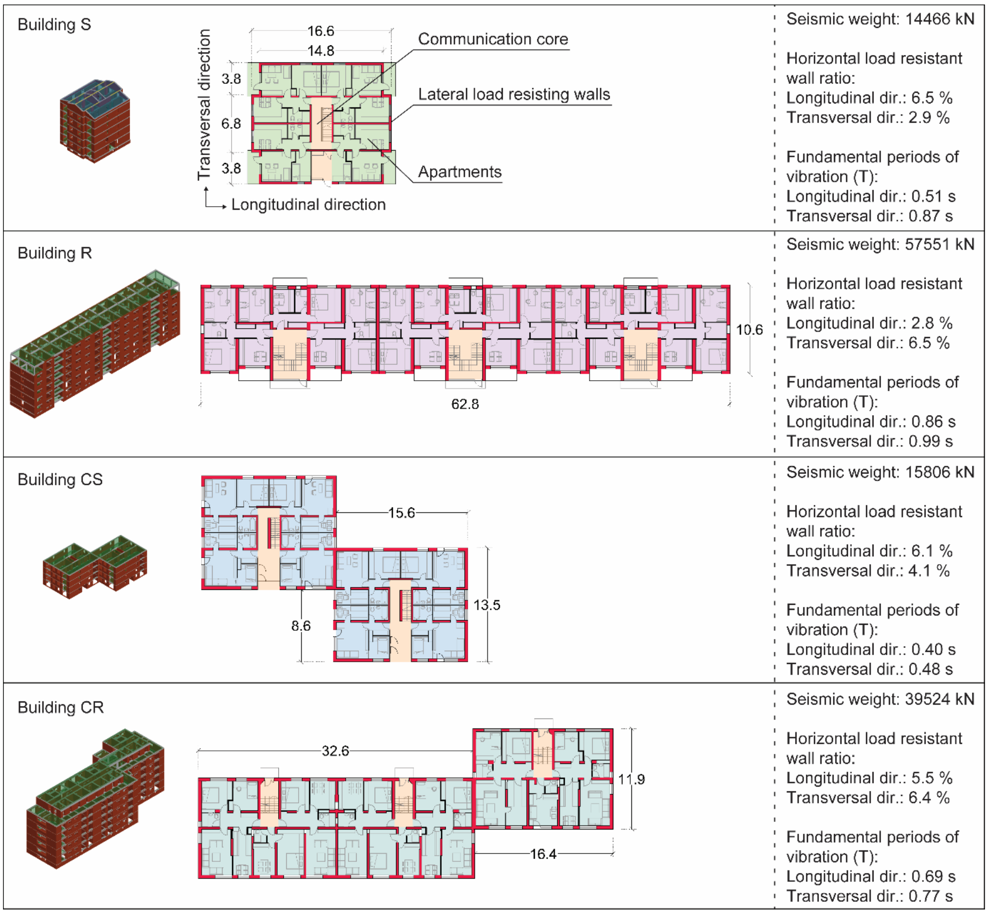

Figure 3: Four representative building prototypes and their key characteristics.

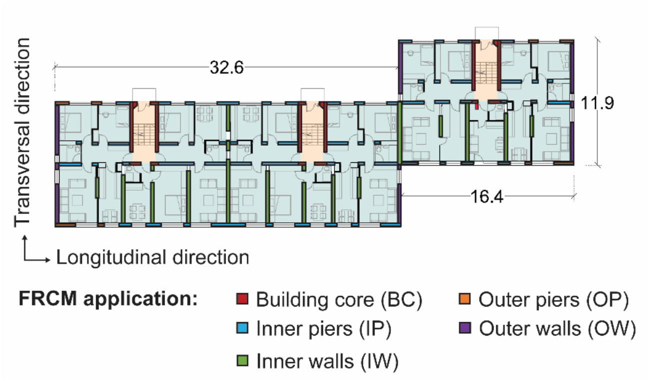

Figure 4: Schematic representation of FRCM retrofit positions for building CR. Similar strengthening configurations were applied to other selected building types.

Material properties of URM were derived from prior studies of similar unreinforced masonry (URM) buildings [14], [15], [16], [17], [18], [19]. These reference values, along with the properties of the FRCM system used in the numerical analysis, are presented in Table 2 and formed the basis for our analyses.

The assessment followed Eurocode 8 – Part 3 guidelines, focusing on two limit states: Damage Limitation (DL) and Significant Damage (SD), corresponding to different levels of structural damage

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and seismic return periods. Lateral load-resistant wall ratios (ρ_w), a key parameter for seismic resistance [20], were calculated for each building typology.

Table 2: Reference mechanical properties of URM and properties of FRCM used in numerical analysis.

URM Properties	
Property	**Reference value**
Compressive strength (f_c)	4.00 MPa
Tensile strength (f_t)	0.14 MPa
Young's modulus (E)	1800 MPa
Shear modulus (G)	360 MPa

Properties of FRCM	
Parameter	**Reference value**
Equivalent thickness of reinforcing mesh (t_f)	0.028 mm
Young's modulus of elasticity of dry fibre (E_f)	280 GPa
Ultimate tensile strain of dry fibres (ε_f)	0.67%
Environmental conversion factor (η_a)	0.8

Building S exhibited higher wall ratios in the longitudinal direction (6.5%) compared to the transversal direction (2.9%) due to its compact and symmetrical configuration. Conversely, Building R showed the reverse trend, with a longitudinal wall ratio of 2.8% versus 6.5% in the transversal direction, attributed to its elongated rectangular shape with numerous openings in the longitudinal facades. These asymmetries suggest potential vulnerabilities requiring targeted strengthening. Building CS displayed a moderate asymmetry in wall ratios (6.1% longitudinal and 4.1% transversal), reflecting its compound square shape with a low slenderness ratio. Despite this, its seismic behaviour appeared balanced, with similar fundamental periods of vibration in both directions. Building CR exhibited near-symmetrical wall ratios (5.5% longitudinal and 6.4% transversal), likely due to its compound rectangular configuration, combining the characteristics of square and rectangular layouts. This balance may contribute to more uniform seismic behaviour, though its geometric complexity could introduce other performance challenges. Overall, the analysis underscored the significance of geometry and wall distribution in seismic vulnerability. Asymmetries in Buildings S and R highlight potential weaknesses, whereas the more balanced configurations in Buildings CS and CR suggest relatively stable performance. However, their intricate geometric layouts could also pose unique challenges that may affect their seismic behaviour in unexpected ways. These insights inform the need for tailored seismic retrofitting strategies to address the unique challenges posed by each typology.

Table 3: Horizontal load resistant retrofitted wall ratio ($\rho_{w,R}$).

	Longitudinal direction		Transversal direction	
Building	**RET**	**RET AW**	**RET**	**RET AW**
S	2.6%	6.5%	1.6%	2.9%
R	1.2%	2.8%	2.7%	6.5%
CS	2.1%	6.9%	1.9%	4.0%
CR	1.2%	5.5%	3.4%	5.9%

The horizontal load-resistant retrofitted wall ratio ($\rho_{w,R}$) was calculated for each building and scenario and is presented in Table 3. The RET-AW scenario consistently resulted in higher $\rho_{w,R}$ values, providing more comprehensive strengthening. However, the RET scenario achieved targeted improvements with reduced intervention, making it a more economical choice in some cases. For instance, Building CR benefited from strategically applied reinforcement in the RET scenario, which effectively addressed vulnerabilities in the longitudinal direction without the extensive disruption associated with RET-AW.

To assess the effectiveness of FRCM retrofitting measures across building typologies and directions, we utilized the seismic performance indicator α, defined as the ratio between d_C and d_D. This ratio provides a clear metric for assessing seismic performance improvement and compliance with EC8-3 requirements for both DL and SD limit states, where $\alpha \geq 1.0$ indicates that the structure meets the code-based compliance criteria. For URM buildings, the α values predominantly fall between 0.30 and 0.60,

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significantly below the required threshold of 1.00, indicating inadequate seismic performance across all examined cases. The effectiveness of the FRCM strengthening system across different building typologies and directions is presented in Table 4. To more accurately assess the impact of the selected retrofitting measures, a new metric (η) was defined as: $\eta = \alpha / \rho_w$ for the case of URM and $\eta = \alpha / \rho_{w,R}$ for the two retrofitted scenarios RET and RET AW. The η ratio normalizes the seismic performance indicator (α) by the total available shear wall ratio (ρ_w) for URM structures, or by the ratio of strengthened walls ($\rho_{w,R}$) for retrofitted scenarios. This normalization allows for a more precise comparison of retrofitting efficiency by considering only the walls that have been strengthened. A higher η value indicates greater effectiveness of the FRCM system relative to the wall area utilized, whether this reflects better inherent seismic performance in URM cases or more substantial performance improvements in retrofitted scenarios.

Table 4: Performance indicator α and retrofitting efficiency metric η.

Principal Direction	Building	Limit State	α [-]			η [-]		
			URM	RET	RET AW	URM	RET	RET AW
Transversal	CR	DL	0.62	0.77	0.81	9.6	22.4	12.6
		SD	0.42	0.47	0.43	6.5	13.5	6.7
	CS	DL	0.31	0.42	0.56	7.7	13.5	13.9
		SD	0.35	0.65	0.72	8.5	21.2	17.8
	R	DL	0.73	0.80	0.85	11.3	29.3	13.2
		SD	0.53	0.81	0.82	8.1	30.0	12.6
	S	DL	0.50	0.56	0.67	17.1	34.0	22.8
		SD	0.75	0.88	0.93	25.6	53.7	31.9
Longitudinal	CR	DL	0.61	0.91	0.96	11.1	76.1	17.6
		SD	0.40	0.51	0.61	7.4	42.1	11.2
	CS	DL	0.40	0.55	0.64	6.6	23.4	10.5
		SD	0.71	0.90	0.97	11.6	38.4	16.0
	R	DL	0.48	0.49	0.64	17.0	40.6	23.0
		SD	0.47	0.58	0.73	16.9	48.0	26.2
	S	DL	0.91	1.10	1.15	14.0	41.7	17.7
		SD	0.55	0.56	0.59	8.5	21.5	9.1

4. Cost-benefit analysis

4.1. Methodological Framework

This study employs a comprehensive methodology for evaluating the economic feasibility of seismic retrofitting measures. The analysis follows a systematic approach that enables detailed building-specific assessments [21].

The cost-benefit analysis process begins with a detailed examination of selected retrofit interventions, particularly focusing on selected FRCM systems with alkali-resistant glass fibre. For each intervention type, we developed a comprehensive list of cost items and their associated unit prices, as presented in Table 6. These baseline costs include material expenses, labour requirements, and auxiliary work such as surface preparation and finishing. The cost estimation first involved detailed quantity surveying for individual prototype buildings, providing precise cost estimates for specific structural configurations.

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4.2. Building Characteristics and Market Values

To establish accurate market values for the analyzed building types, we utilized data from the Real Estate Market Register (ETN) maintained by the Surveying and Mapping Authority of the Republic of Slovenia [22]. The ETN database provides a comprehensive and reliable foundation for market value assessment, capturing at least 95% of all real estate transactions in Slovenia. The property values presented in Table 5 represent median prices derived from actual transactions, offering a balanced view where half of the transactions fall above and half below these reference points.

Our analysis reveals significant variations in both apartment sizes and market values across the four building typologies. Building R contains the largest apartments with a mean floor area of 56.6 m², while Building CS features notably smaller units averaging 40.2 m². Buildings S and CR fall between these extremes, with mean apartment sizes of 49.9 m² and 53.0 m² respectively. These size variations reflect the different architectural approaches and social priorities of post-war residential development.

Market prices per square meter demonstrate equally noteworthy differences among the building types. Building CS commands the highest value at 3833.9 €/m², suggesting strong market appreciation for its architectural characteristics and location. In contrast, Building R exhibits the lowest market value at 2832.4 €/m², while Buildings S and CR maintain intermediate positions at 3253.1 €/m² and 3169.5 €/m² respectively. These price variations likely reflect a combination of factors including location, building condition, and local market dynamics.

The reliability of these market value assessments is strengthened by the ETN's comprehensive coverage of the real estate market and its standardized methodology for recording and analyzing transaction data. These baseline values prove essential for our subsequent analysis of retrofitting costs and their economic implications, allowing us to evaluate the financial feasibility of different intervention strategies in relation to current property values. This market context becomes particularly relevant when considering the substantial investments required for seismic retrofitting and their potential impact on property values.

Table 5: Apartment size and mean market price.

Building	Total floor area of apartments [m²]	Mean floor area of single apartment [m²]	Mean market value per square meter [€/m²]
S	998.0	49.9	3253.1
R	1286.4	40.2	2832.4
CS	3058.8	56.6	3833.9
CR	2542.8	53.0	3169.5

4.3. Building-Specific Cost Analysis and Economic Performance Indicators

The detailed cost analysis was conducted for both retrofitting scenarios (RET and RET-AW) across all four prototype buildings, considering their specific geometric characteristics and apartment configurations. The analysis incorporated both the base retrofit costs and an optional thermal insulation component (TI), though our primary focus remains on the seismic strengthening aspects.

Using the unit costs from Table 6, which includes basic operations like plaster removal (16 €/m²), FRCM system installation (120 €/m²), and finishing works, we calculated the total intervention costs per square meter of net apartment area. As shown in Figure 5, the results demonstrate significant variations across building types and retrofitting scenarios. For the RET scenario without thermal insulation, Building S exhibits costs of 276.3 €/m² of net apartment area, while Buildings CS, R, and CR show costs of 299.6 €/m², 191.3 €/m², and 186.7 €/m² respectively. The addition of thermal insulation (TI) increases these costs by approximately 30%.

The more comprehensive RET-AW scenario naturally results in higher costs across all building types, as illustrated by the orange bars in Figure 5. Without thermal insulation, Building S requires 599.6 €/m²,

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Building CS needs 584.3 €/m², Building R demands 642.0 €/m², and Building CR requires 585.0 €/m². Again, the inclusion of thermal insulation further increases these costs.

Table 6: Retrofitting measures - cost items and unit prices.

Cost item	Cost €/m²
FRCM system	120.00
Removal of existing plaster	16.00
Plaster finishing (internal / external)	12.00
Wall painting (internal / external)	2.50
Thermal insulation (optional cost)	52.00

Figure 5 also presents the relationship between retrofit costs and the efficiency metric η for the Significant Damage (SD) limit state. The solid lines show efficiency in the longitudinal direction, while the dashed lines represent the transverse direction. Interestingly, the RET scenario often achieves higher η values despite lower absolute costs, particularly in the longitudinal direction, suggesting better cost-effectiveness of targeted interventions.

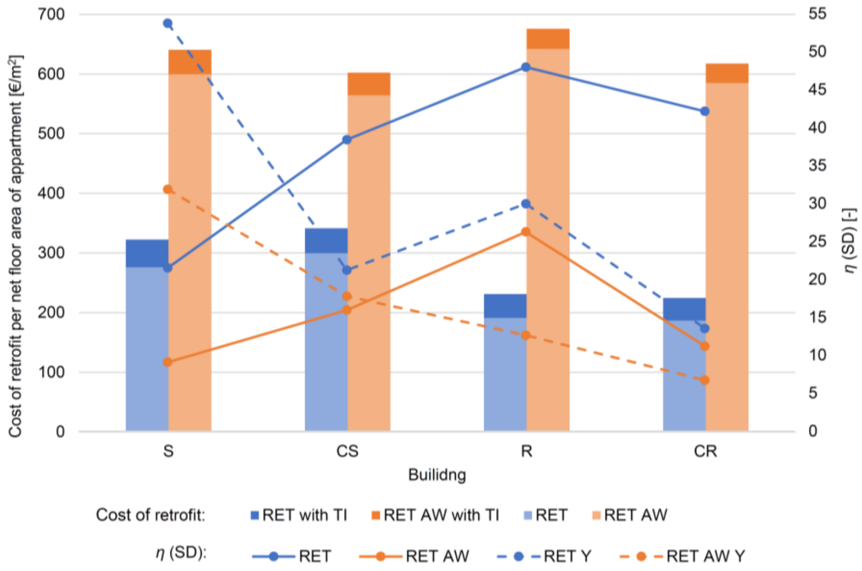

Figure 5: Correlation between retrofit cost and η.

When comparing these costs to current market values, Figure 6 reveals the retrofitting investments as percentages of property value. For the basic RET scenario, the investment ranges from about 5% to 8% of current market value. Adding thermal insulation increases this to 6-10%. The more extensive RET-AW scenario requires significantly higher investments, ranging from 17% to 23% without thermal insulation, and reaching up to 24% with thermal insulation included. This substantial difference in investment requirements highlights the importance of careful consideration when selecting retrofitting strategies.

The analysis reveals that buildings with higher initial market values (like Building CS at 3833.9 €/m²) tend to justify more comprehensive retrofitting strategies, as the relative cost impact remains manageable while providing enhanced structural safety. Conversely, buildings with lower market values may benefit more from targeted interventions that optimize the cost-benefit ratio. This finding suggests that strategic placement of strengthening measures may offer a more economically viable approach to seismic risk mitigation, particularly for buildings with limited financial resources for renovation.

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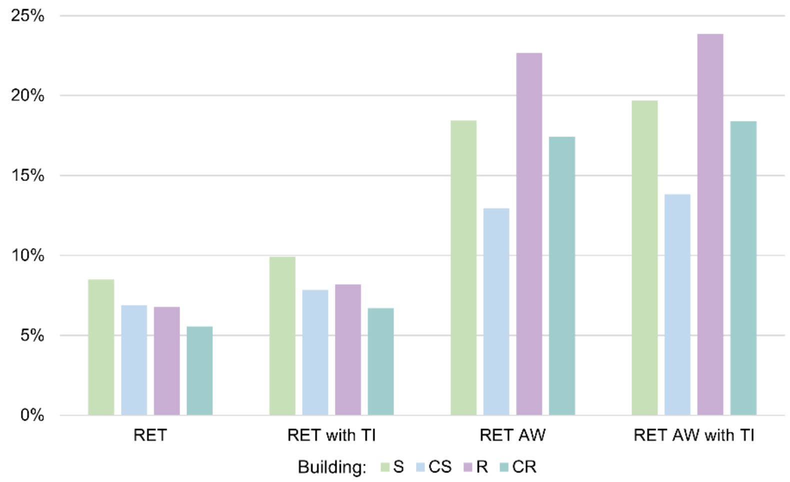

Figure 6: Retrofit cost as percentage of apartment market value.

5. Conclusions

This study provides valuable insights into the economic feasibility and structural effectiveness of FRCM retrofitting for post-war masonry buildings in Ljubljana. The cost analysis reveals that selective retrofitting (RET) requires investments ranging from 5-8% of current property values, while comprehensive strengthening (RET-AW) demands 17-23%. When considering the efficiency metric η, the RET scenario demonstrates higher values despite lower absolute costs, suggesting better cost-effectiveness of targeted interventions versus full-building strengthening.

However, the seismic performance analysis indicates that FRCM strengthening alone may be insufficient to achieve full EC8-3 compliance. While several retrofitted configurations achieve α values between 0.6 and 0.8 for both damage limitation (DL) and significant damage (SD) limit states, only one case reaches α ≥ 1.0 (Building S, longitudinal direction, DL state). This suggests that additional rigorous strengthening measures, such as the addition of new structural walls or cores, may be necessary to meet current seismic code requirements. Future research should explore combining FRCM with other retrofit techniques to achieve both economic feasibility and adequate seismic performance.

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References

[1] Brzev, S., Blagojević, P., & Cvetković, R. (2023): Seismic retrofitting of post-WWII mid-rise unreinforced masonry residential buildings in the Balkans, *2nd Croatian Conference on Earthquake Engineering - 2CroCEE*, Zagreb, Croatia. doi: https://doi.org/10.5592/CO/2CroCEE.2023.90

[2] Atalić, J., Šavor Novak, M., & Uroš, M. (2019): Seismic risk for Croatia: Overview of research activities and present assessments with guidelines for the future. Građevinar, 71, 923-947. doi: https://doi.org/10.14256/JCE.2732.2019

[3] Kilar, V., & Kušar, D. (2009): Assessment of the earthquake vulnerability of multi-residential buildings in Slovenia. *Acta Geographica Slovenica*, 49(1). doi: https://doi.org/10.3986/ags49103

[4] Petrovski, J.T. (2004). Damaging effects of July 26, 1963 Skopje earthquake. Middle East Seismological Forum, Cyber Journal of Geoscience, Volume Two.

[5] Lagomarsino, S., Penna, A., Galasco, A., & Cattari, S. (2013): TREMURI program: an equivalent frame model for the nonlinear seismic analysis of masonry buildings, *Engineering Structures*, 56, 1787-1799. doi: https://doi.org/10.1016/j.engstruct.2013.08.002

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.85

[6] Petelin, D. (2017): Stanovanjske razmere v Ljubljani v letih 1945–1965. *Kronika*, 65(1), 1-18. [In Slovenian].

[7] Nikšič, M., Goršič, N., Mihelič, B., Mujkić, S., & Tominc, B. (2013): Smernice za vzdrževanje in prenovo karakterističnih območij mesta Ljubljane, Litostrojsko naselje. Mestna občina Ljubljana. [In Slovenian].

[8] Nikšič, M., Goršič, N., Mihelič, B., Mujkić, S., & Tominc, B. (2013): Smernice za vzdrževanje in prenovo karakterističnih območij mesta Ljubljane, Savsko naselje. Mestna občina Ljubljana. [In Slovenian].

[9] Prašnikar, P., Kilar, V., Petrovčič, S. (2024): Typology and seismic assessment of multi-residential post-war masonry buildings in Ljubljana, *18th World Conference on Earthquake Engineering*, Milan, Italy.

[10] Petrovčič, S., Kilar, V., Prašnikar, P., Azinović, B., Bradeško, T., Gjura Godec, M., Grulja, S.N., Krznarič, E., Anil, A., Rogelj, J.: Project results "Aggregation of data on post-war architectural structures in Slovenia for the assessment of their seismic resistance", University of Ljubljana Repository, https://repozitorij.uni-lj.si/IzpisGradiva.php?lang=slv&id=164800, Version: 01.12.2023, (accessed December 15, 2024).

[11] Uroš, M., Demšić, M., Šavor Novak, M., Atalić, J., Baniček, M., Jevtić Rundek, R., & Prevolnik, S. (2024): Damage Evaluation and Seismic Assessment of a Typical Historical Unreinforced Masonry Building in the Zagreb 2020 Earthquake: A Case Study—Part I. *Buildings*, 14(2), 474. doi: https://doi.org/10.3390/buildings14020474

[12] CNR (2018): Guide for the Design and Construction of Externally Bonded Fibre Reinforced Inorganic Matrix Systems for Strengthening Existing Structures. Advisory Committee on Technical Recommendations for Construction, Rome, Italy.

[13] Petrovčič, S., Prašnikar, P., & Kilar, V. (2023): Seismic Performance and Retrofit of a Mid-Rise Post-second World War Residential Building Made of Unreinforced Masonry, *13th International Conference on Structural Analysis of Historical Constructions*, Kyoto, Japan. pp. 929-943. doi: https://doi.org/10.1007/978-3-031-39603-8_75

[14] Bosiljkov, V., Antolinc, D., Čepon, F., Jursinovič, B., Siebenreich., N. (2016): Poročilo o analizi nosilnosti in potresne odpornosti objekta UL ALUO na Erjavčevi 23 v Ljubljani. *Report No. P 001/3/16*, University of Ljubljana, Faculty of Civil and Geodetic Engineering [In Slovenian], Ljubljana, Slovenia.

[15] Lutman, M. (2018): Ocena potresne ogroženosti stavbe Praprotnikova ulica 15 v Ljubljani. *Report No. P 331/18-610-1*, Slovenian National Building and Civil Engineering Institute [In Slovenian], Ljubljana, Slovenia.

[16] Bilgin, H., & Huta, E. (2018): Earthquake performance assessment of low and mid-rise buildings: Emphasis on URM buildings in Albania. *Earthquakes and Structures*, 14(6), 599–614. doi: https://doi.org/10.12989/EAS.2018.14.6.599

[17] Mendes, N., & Lourenço, P.B. (2014): Sensitivity analysis of the seismic performance of existing masonry buildings. *Engineering Structures*, 80, 137-146. doi: https://doi.org/10.1016/j.engstruct.2014.09.0055

[18] Bompa, D.V., & Elghazouli, A.Y. (2020): Compressive behaviour of fired-clay brick and lime mortar masonry components in dry and wet conditions. *Materials and Structures*, 53(3), 60. doi: https://doi.org/10.1617/s11527-020-01493-w

[19] Soleymani, A., Najafgholipour, M.A., & Johari, A. (2022): An experimental study on the mechanical properties of solid clay brick masonry with traditional mortars. *Journal of Building Engineering*, 58, 105057. doi: https://doi.org/10.1016/j.jobe.2022.1050577

[20] Blagojević, P., Brzev, S., & Cvetković, R. (2021): Simplified seismic assessment of unreinforced masonry residential buildings in the Balkans: The case of Serbia. *Buildings*, 11(9), 392. doi: https://doi.org/10.3390/buildings11090392

[21] Follador, V., Donà, M., Carpanese, P., Saler, E., D'Alpaos, C., & da Porto, F. (2024): Seismic retrofit cost model for Italian masonry residential buildings to support territorial-scale risk analysis, *International Journal of Disaster Risk Reduction*, 105, 104373. doi: https://doi.org/10.1016/j.ijdrr.2024.104373

[22] Geodetska uprava Republike Slovenije. Trg nepremičnin. Dostopno na: https://www.e-prostor.gov.si/podrocja/trg-in-vrednosti-nepremicnin/trg-nepremicnin/?acitem=1967-2418 (accessed June 6, 2024).