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SEISMIC RISK AND LOSS ASSESSMENT OF REINFORCED CONCRETE FRAME STRUCTURES STRENGTHENED BY THE ADDITION OF MASONRY INFILL WALLS

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Abstract

This study addresses the behaviour of bare plane RC frames and RC frames strengthened by the addition of masonry infill in combination with the connection of infill and frame elements for earthquake action. The main objective was to explore the possibilities of using infill walls in RC frames as a strengthening method, observing the in-plane cyclic responses obtained through experimental tests on specific specimens. The experimental part of the study was carried out on 10 single-bay, single-storey specimens of ductile and RC frames strengthened with masonry infill (hollow clay block and solid clay brick units) of which 3 reference samples were used to evaluate the strengthening of the infill and the quality of the interconnection between the infill and the frame. The frame specimens are built to a scale of 1:2.5 and tested under constant vertical and horizontal cyclic loading. The test specimens can be grouped according to the type of infill (hollow clay block and solid clay brick units) and the type of connection between the infill and the frame. The same preliminary simplified calibration with non-linear macro models in OpenSees was performed for all test specimens for which satisfactory responses to cyclic responses were obtained compared to the experiments. The same models were used in the numerical case study for predicting the dynamic response to the application to a case study building through Incremental Dynamic Analysis (IDA), where IDA curves, fragility functions, vulnerability and loss curves, and risk measures such as Expected Annual Loss (EAL) and mean annual frequency of collapse (λ_C) were created separately for each type of strengthening to evaluate the efficiency of a particular strengthening compared to reference models.

Keywords: RC frames, Masonry infill, Seismic strengthening, Numerical modelling, Incremental Dynamic Analysis (IDA), Risk and loss assessment.

1. Introduction

Masonry-infilled reinforced concrete (RC) frames are extensively utilized structural systems, particularly prevalent in Southern and Eastern Europe. They significantly contribute to a structure's lateral stiffness and strength, essential characteristics for resisting seismic loads [1,2]. The complex and highly nonlinear interaction between masonry infill walls and RC frames has been the subject of considerable research. Despite this, accurately capturing this interaction remains a substantial engineering challenge, often resulting in the exclusion of infill contributions during structural design, seismic evaluations, and retrofitting procedures [3,4]. This omission is particularly concerning because masonry infills, when appropriately designed and distributed, can provide beneficial effects like shear walls, enhancing structural performance under seismic conditions. Conversely, their uneven distribution or partial inclusion within a structure may result in detrimental effects, potentially leading to localized structural failures and significant performance degradation [5,6].

Masonry infills are frequently chosen for their advantageous economic and physical characteristics, such as affordability, high thermal and acoustic insulation, fire resistance, and durability [7,8]. However, their inherent brittleness and high stiffness can result in substantial damage even in moderate earthquakes, leading to significant repair costs, building downtime, and increased risk to human safety [9–12]. Post-earthquake assessments repeatedly demonstrate that non-structural elements, especially masonry infills and partition walls, constitute the largest portion of repair and restoration expenses, highlighting their critical role in overall building seismic performance [1–4].

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Consequently, researchers have explored various strategies aimed at improving the seismic performance of masonry-infilled RC frames. Among these strategies, strengthening methods using reinforced masonry infills have gained significant attention due to their potential to enhance both stiffness and ductility of existing structures [13–18]. Such traditional strengthening approaches generally involve reinforcing existing infill walls or constructing new ones that are structurally integrated with the RC frames, thereby optimizing their beneficial properties and reducing vulnerability.

Nonetheless, despite significant advancements in experimental and numerical research, comprehensive probabilistic assessments that integrate seismic risk, reliability, and economic implications remain relatively limited [24–26]. Performance-based earthquake engineering (PBEE) methodologies, particularly incremental dynamic analysis (IDA), offer robust frameworks for evaluating these aspects. IDA-based assessments enable detailed comparison of structural fragility, risk—expressed as mean annual frequency of collapse (λ_C), and associated seismic losses—expressed quantitatively as Expected Annual Loss (EAL)—thus providing critical insights into the benefits and trade-offs associated with different seismic strengthening strategies using masonry infills [24,27,28].

This paper extends the current state-of-the-art by systematically examining the seismic performance of RC frames strengthened using traditional masonry infills. Employing IDA-based methodologies, coupled with comprehensive fragility, hazard, risk, and loss analyses, this study aims to clearly quantify and validate the effectiveness of masonry infills as a seismic retrofitting and strengthening solution.

2. Strengthening techniques

Enhancing seismic resistance of existing reinforced concrete (RC) structures is vital for their safety and operational functionality during earthquakes. Seismic upgrading techniques typically fall into two broad categories: local measures, applied to individual structural elements, and global measures, applied to the structure. Local measures typically involve adding external reinforcement to existing structural elements, enhancing flexural and shear capacities, and ductility. When significant improvements in lateral load capacity or stiffness are needed, local methods alone might be inadequate or economically inefficient. In such cases, global strengthening strategies are employed, aiming either to enhance the structure's overall lateral strength and stiffness or reduce the seismic forces acting on it. Increasing lateral strength and stiffness often involves the introduction of new structural elements, significantly boosting lateral resistance. Alternatively, seismic demand can be mitigated through base isolation systems or energy-dissipating devices. This study specifically focuses on global strengthening approaches involving the addition of masonry infill walls to existing RC frames, as investigated experimentally by Grubišić et al. [29,30]. The effectiveness of these masonry infill walls in strengthening RC frames is assessed in terms of their capacity to enhance structural performance under seismic loading conditions [29,30].

2.1. Test specimens

Experimental tests were performed on RC frame specimens strengthened using masonry infill walls. Specimens were constructed using hollow clay blocks or solid clay bricks with general-purpose cement-lime mortar (strength class M5, minimum compressive strength after 28 days: 5 N/mm²), complying with standard requirements for masonry structures (Eurocode 6). All details regarding the test specimens, testing protocol, material properties, and cyclic static responses are presented and thoroughly explained by Grubišić [30]. The tested specimens included (Figure 1):

- TYPE 1/I – Infilled ductile RC frame, hollow clay blocks with steel dowels.
- TYPE 2/I – Infilled ductile RC frame, reinforced hollow clay blocks with steel dowels.
- TYPE 3/I – Infilled ductile RC frame, hollow clay blocks with vertical confinement and steel dowels.
- TYPE 1/II – Infilled ductile RC frame, solid bricks with steel dowels.
- TYPE 2/II – Infilled ductile RC frame, reinforced solid bricks with steel dowels.

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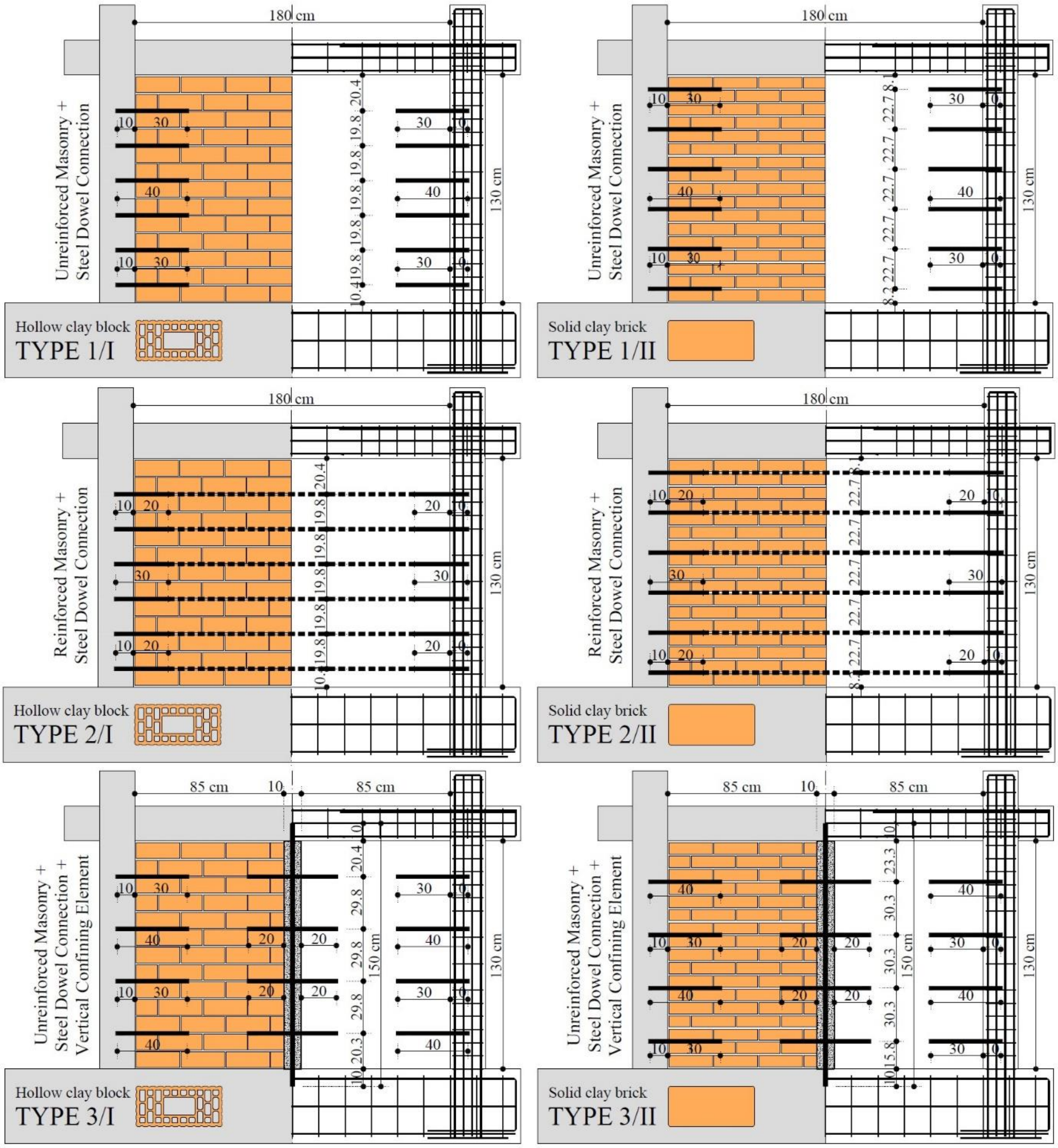
- TYPE 3/II – Infilled ductile RC frame, solid bricks with vertical confinement and steel dowels.
- TYPE 4 – Infilled ductile RC frame, hollow clay blocks with ECC composite (one side) and steel dowels.
- TYPE 5 – Infilled ductile RC frame, hollow clay blocks with FRP composite (one side) and steel dowels.
- TYPE 6 – Infilled non-ductile RC frame #1, solid bricks with ECC composite (both sides) and steel dowels.
- TYPE 7 – Infilled non-ductile RC frame #2, solid bricks with ECC composite (both sides) and steel dowels.
- TYPE 8/REF – Infilled ductile RC frame, hollow clay blocks (reference specimen).
- TYPE 9/REF – Infilled ductile RC frame, solid bricks (reference specimen).
- TYPE 10/REF – Bare ductile RC frame (reference specimen).



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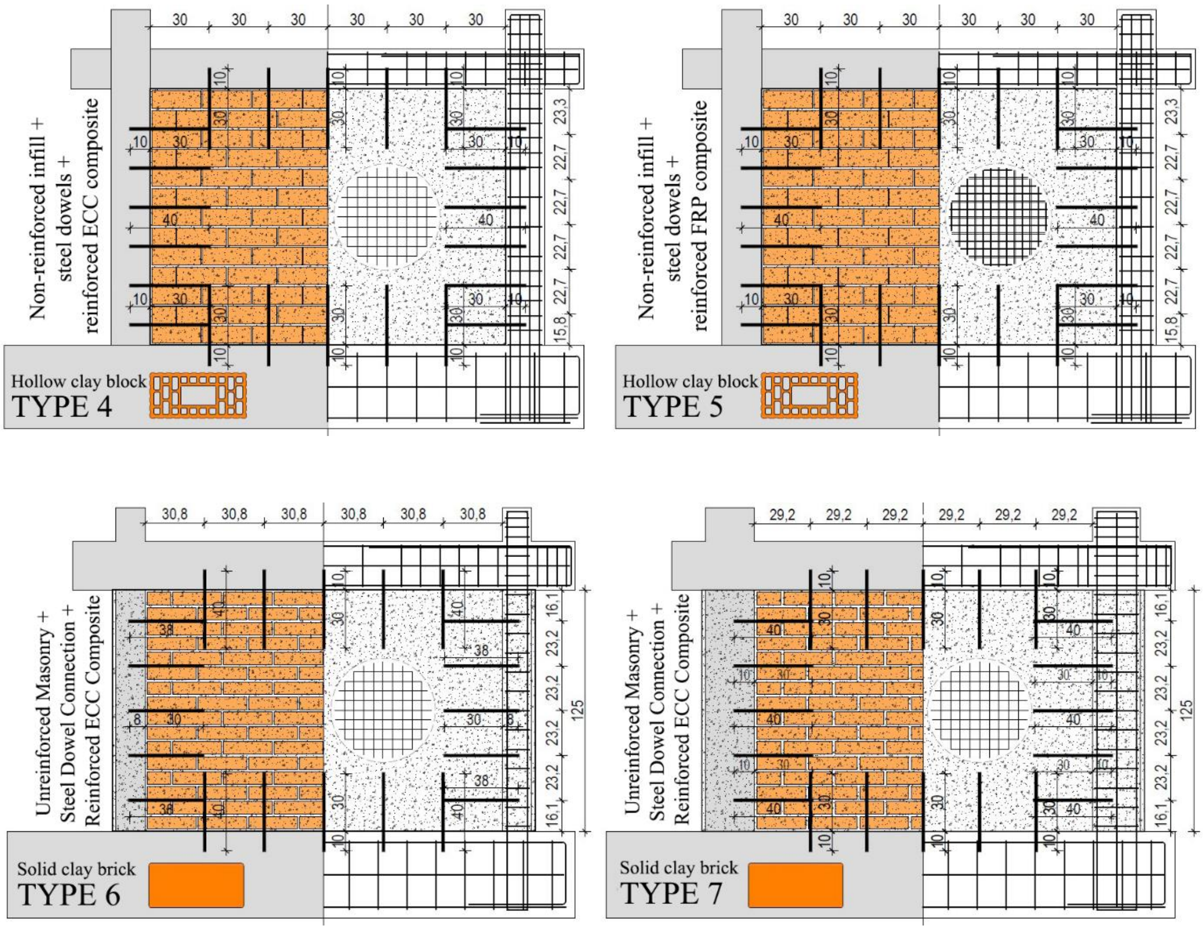

Figure 1. The applied methods of the masonry infill walls. Strengthening methods are shown with and without reinforcement details, i.e., the specimens do not contain any openings.

3. Seismic Risk and Loss Assessment procedure

Performance-Based Earthquake Engineering (PBEE) encompasses a comprehensive framework for the design, evaluation, construction, and maintenance of structures to meet specific performance objectives under seismic conditions. According to Krawinkler and Miranda [32,33], PBEE is based on predicting structural performance with quantifiable confidence, enabling informed decisions and trade-offs considering life-cycle costs rather than initial construction expenses alone. The PBEE methodology integrates seismic hazard assessment, structural response analysis, damage analysis, and loss estimation, explicitly accounting for uncertainties at each stage (Figure 2 and 3).

The FEMA P-58 procedure [34], a widely adopted approach within PBEE, allows clear quantification of seismic performance using comprehensible variables such as economic losses, casualties, and downtime. The inherent uncertainties are explicitly incorporated through Probabilistic Seismic Hazard Analysis (PSHA), structural analysis via Incremental Dynamic Analysis (IDA), damage estimation using fragility curves, and finally loss assessment through specific loss functions. Each step involves distinct performance indicators: Intensity Measure (IM), Engineering Demand Parameters (EDP), Damage Measures (DM), and Decision Variables (DV).

The mathematical formulation of PBEE provided by FEMA P-58 employs the total probability theorem, summarised in Equation 1:

$$\lambda(DV) = \iiint G(DV \mid DM), \mathrm{d}G(DM \mid EDP), \mathrm{d}G(EDP \mid IM), \mathrm{d}\lambda(IM) \tag{1}$$

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where:

- $\lambda(DV)$ is the mean annual frequency of exceeding a specific Decision Variable (DV), such as economic loss, downtime, or casualties.
- $G(DV|DM)$, $G(DM|EDP)$, and $G(EDP|IM)$ represent conditional cumulative distribution functions linking DV to DM, DM to EDP, and EDP to IM, respectively.
- $\lambda(IM)$ denotes the mean annual frequency of exceeding an Intensity Measure (IM) derived from PSHA.

This equation effectively compartmentalises seismic risk assessment into four sequential stages: hazard characterisation, structural response evaluation, damage assessment, and economic loss estimation. Each stage provides a transparent and structured approach to quantify uncertainties and aids engineers and stakeholders in making informed, rational decisions regarding seismic risk management strategies.

Incremental Dynamic Analysis (IDA) quantifies uncertainties in EDP using various seismic excitations. Damage uncertainties are captured via fragility curves, relating the probability of damage states to EDP. Economic losses, casualties, and downtime uncertainties are represented through loss functions conditioned on specific damage states. Mean annual frequencies of decision variables are computed via integration considering IM, EDP, DM, and DV uncertainties, providing robust means to communicate seismic risks clearly.

In this study, the FEMA P-58 methodology is adopted to evaluate and quantify the seismic performance of RC frame structures strengthened using traditional masonry infill walls, contributing significantly to existing research by providing detailed insights into seismic resilience and cost-effectiveness.

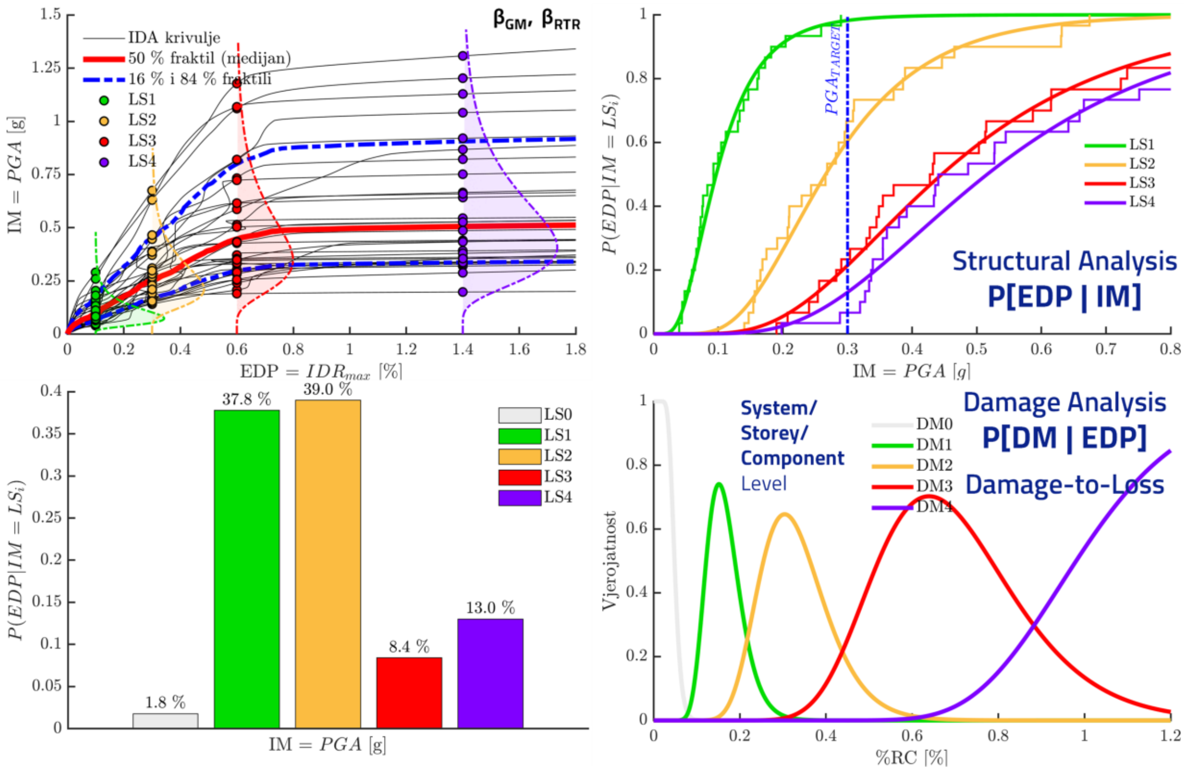

Figure 2. Illustrated steps in probabilistic seismic risk analysis and loss assessment of individual buildings, according to Performance-Based Earthquake Engineering (PBEE) and the FEMA P-58 procedure.

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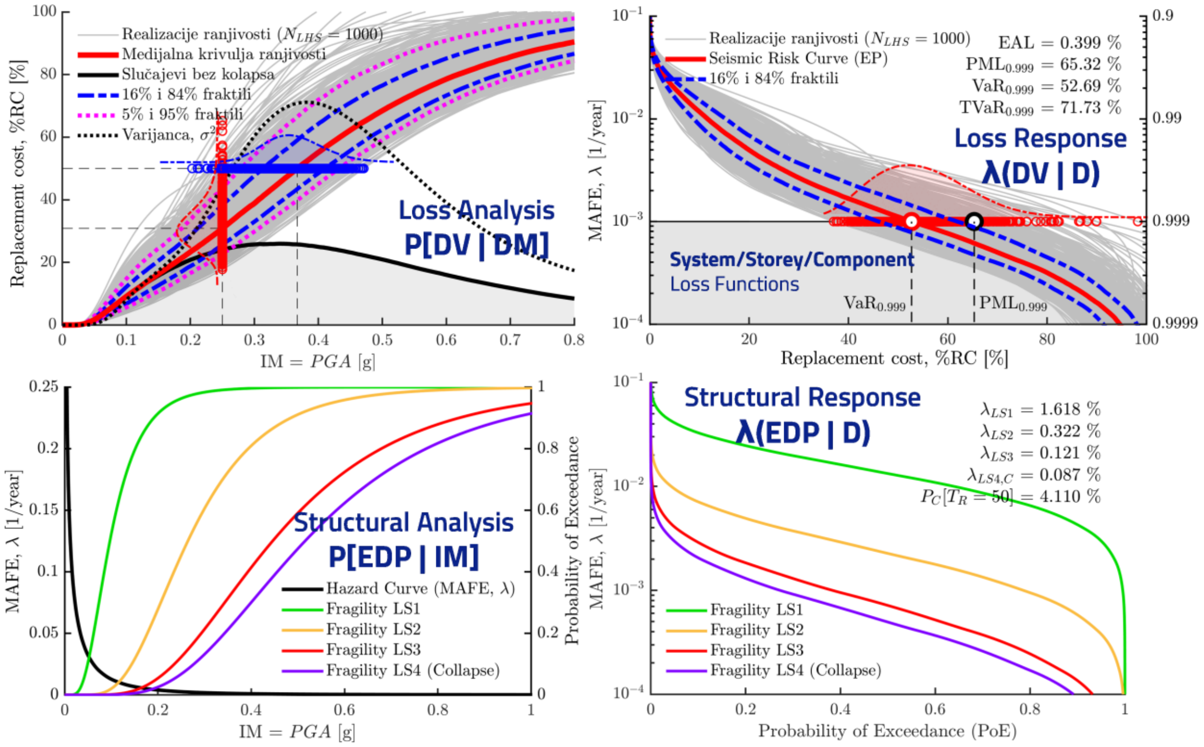

Figure 3. Illustrated steps in probabilistic seismic risk analysis and loss assessment of individual buildings, according to Performance-Based Earthquake Engineering (PBEE) and the FEMA P-58 procedure.

4. Numerical Case Study and Performance Assessment

All numerical models were constructed and analysed in OpenSees and are based on all original calibrated parameters based on previously described experiments, discussed in detail earlier by Grubišić [30]. The structure selected for this numerical case study is a reinforced concrete (RC) frame building designed according to Eurocode 8. The same RC structural configuration was consistently used for all 12 numerical models, differentiated solely by masonry infill and strengthening characteristics. The chosen building replicates the geometry of the Tsukuba building, previously subjected to pseudo-dynamic experimental testing. This building was selected due to the similarity of its geometry and load analysis to the experimental models discussed in previous sections. Detailed information about the basic RC structural system is available in earlier research by Grubišić [30]. From the total of 13 experimental models described previously, 12 numerical models were developed for this study. The numerical models of this case study present the same design properties of the models of the same name described earlier, by means of description and notation.

From the original three-dimensional Tsukuba model, the most heavily loaded representative internal planar frame in the longitudinal direction was isolated for numerical analysis. The selected frame consists of spans measuring 6 m, 5 m, and 6 m, with storey heights of 3.75 m for the ground floor and 3 m for upper floors. RC slabs are 18 cm thick; columns measure 50×50 cm, and beams measure 30×50 cm. Reinforcement detailing for columns and beams is illustrated in Figure 4. Materials used include concrete class C30/37 and reinforcing steel class B500B. All frame elements were designed according to standard vertical and horizontal seismic loading with peak ground acceleration (PGA) of 0.35 g, complying with Eurocode 8 requirements for seismic zone conditions in Croatia.

In terms of dynamic properties, nodal masses were uniformly concentrated at frame nodes, with total values of 16.5 and 27 tonnes at external and internal ground nodes respectively, 18.2 and 28.6 tonnes at upper floors, and 19.3 and 31.7 tonnes at roof nodes. Masonry infill walls were introduced using hollow clay blocks and solid clay bricks bonded by cement-lime mortar (strength class M5) with a

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mortar joint thickness of 1 cm. Detailed material properties for masonry units, mortar, and frame-infill connections were adopted from experimental data. Masonry infills and their connections were implemented consistently across the central bay of each frame.

Numerical modelling adopted a concentrated plasticity approach, defining rotational springs with specific hysteretic behaviour at beam-column joints. Masonry infills were simulated by equivalent diagonal struts representing compression and tension, reflecting their mechanical interaction with the surrounding frame. Beam and column joint details conformed to Eurocode 8. The numerical models were analysed to evaluate displacement capacity, energy dissipation, and fundamental vibration periods. Probabilistic seismic analyses were performed to estimate seismic vulnerability, considering randomness in seismic excitation and calculating exceedance probabilities for specific damage states. A two-dimensional analysis framework was adopted, offering simplicity, robustness, and reliability in seismic performance assessment.

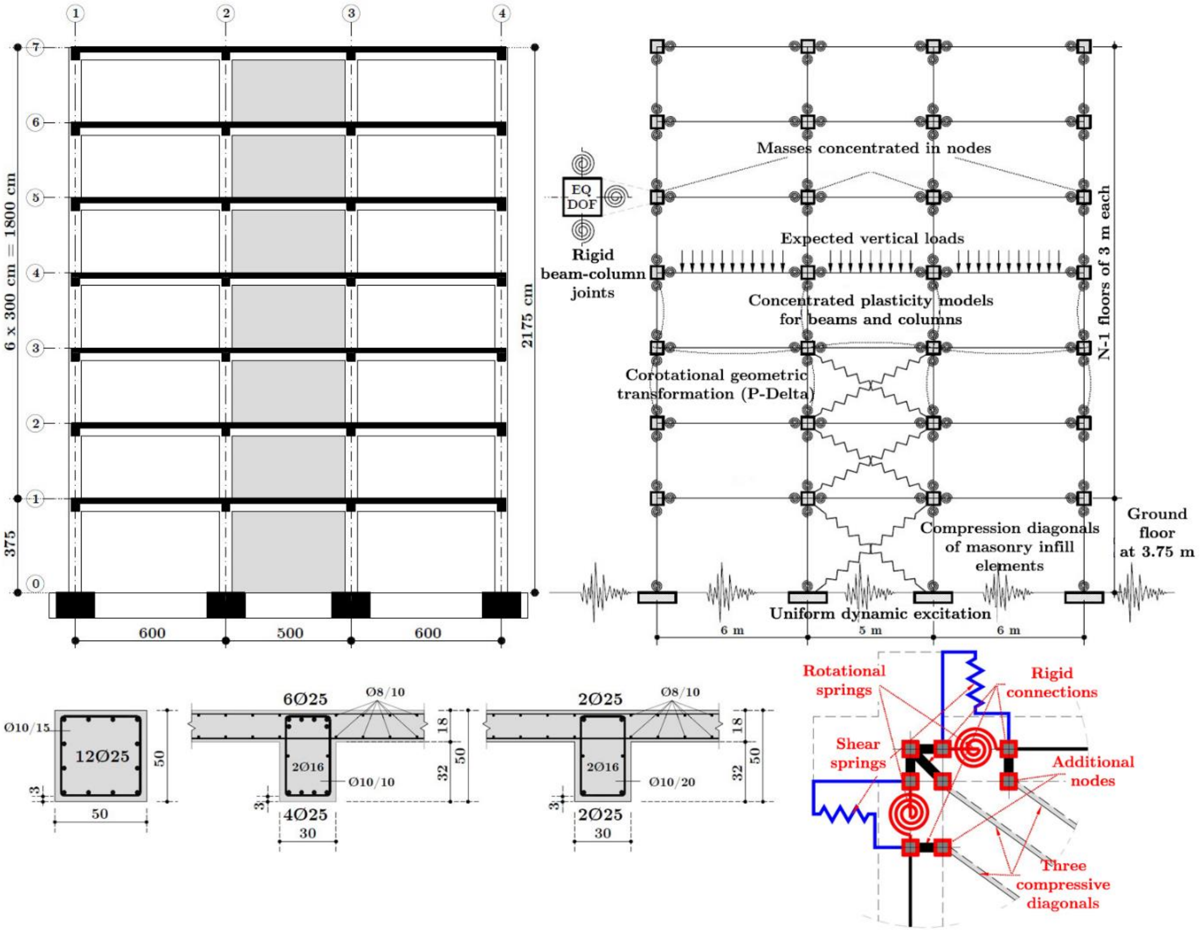

Figure 4. Reinforcement configuration in cross-sections of column ends, or ends and half of beam spans, obtained by designing the structure according to Eurocode 8.

After defining the hazard curve for a selected intensity measure (e.g., spectral acceleration, $S_A(T_1, 5\%)$), the disaggregation of seismic hazard can be analysed for a return period of 475 years (Figure 5, left). For this numerical study, 30 real ground-motion records were selected from the PEER NGA West 2 database. These records were chosen to closely match the mean target spectrum within the expected natural vibration period range of the studied numerical models (Figure 5, right).

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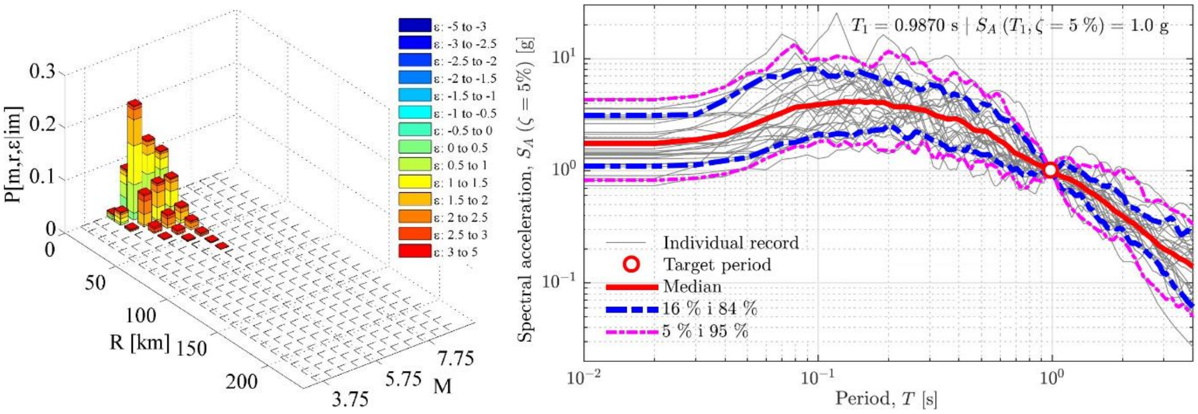

Figure 5. Disaggregation of seismic hazard for the building location (left); 30 real ground-motion records chosen to closely match the mean target spectrum (right).

5. Seismic Risk and Loss Assessment Results

This section presents a brief overview of the key findings derived from the numerical modelling, risk analyses and loss assessment. Figure 6 illustrates the median 5% damped spectral acceleration at the structure's first-mode period, $S_A(T_1, 5\%)$, for all numerical models examined. Specifically, the left figure depicts the median $S_A(T_1, 5\%)$ at the point of structural collapse, providing insight into the seismic intensity required to induce failure. Conversely, the right figure presents the median $S_A(T_1, 5\%)$ corresponding to a 50% loss ratio, indicating the intensity associated with significant, though not complete, structural damage. Figure 7 presents the discrete probability distribution of limit state regions. This distribution is derived from the fragility curve analysis, which quantifies the likelihood of the structure exceeding predefined damage states under varying seismic intensities. The figure visually represents the probabilistic assessment of the structure's vulnerability to different levels of seismic demand. Figure 8 displays the mean annual frequency of collapse, λ_C, on the left. This metric represents the expected number of collapse events per year, providing a crucial measure of the structure's collapse risk. Figure 8 displays the mean annual frequency of collapse (λ_C) on the left, representing the expected number of collapse events per year, and the average annual loss ratio (AAL) on the right, quantifying expected annual economic loss as a fraction of total replacement cost (RC).

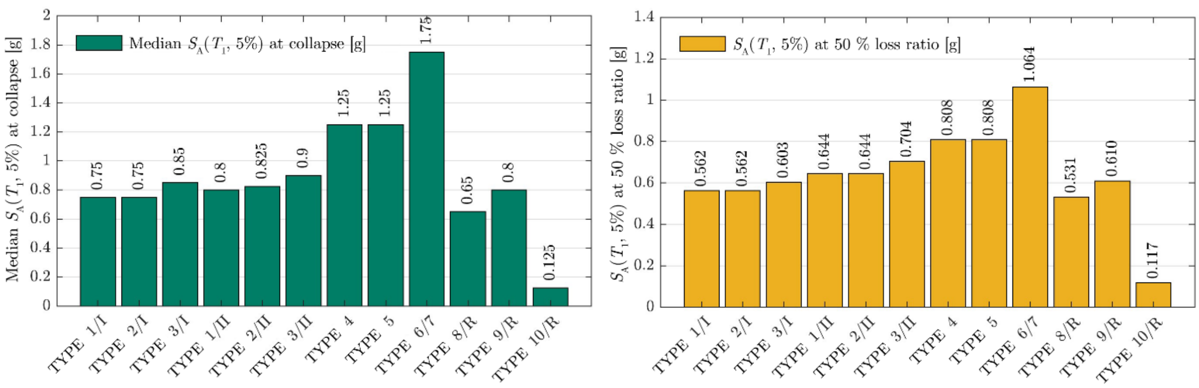

Figure 6. Median $S_A(T_1, 5\%)$ at collapse (left) and $S_A(T_1, 5\%)$ at 50% loss ratio (right) for all numerical models analysed

Based on these analyses, the following conclusions regarding the efficiency of various strengthening techniques can be drawn:

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- The most vulnerable model is clearly the empty RC frame (TYPE 10/REF), as it demonstrates the lowest horizontal load capacity and the highest deformation. This model can sustain the lowest spectral acceleration levels, with nearly a 49% probability of collapse and a 37% probability of reaching the LS4 (near-collapse) limit state, according to the hazard curve based on the set of 30 earthquake records. TYPE 10/REF experiences approximately six times greater average annual losses (AAL) and almost eight times higher mean annual frequency of collapse (λ_C) compared to other models.
- Models TYPE 1/I, 2/I, 3/I, 1/II, 2/II, and 3/II exhibit relatively similar horizontal load capacities and ductilities. Considering spectral acceleration as a measure of intensity at 50% vulnerability, the type of masonry unit (solid brick versus hollow clay block) has a more significant impact than the presence of vertical confinement. Losses and vulnerabilities are quite similar for these six models. However, TYPE 3/II is favoured due to the robustness of the solid brick elements combined with vertical confinement, providing up to 15% higher spectral acceleration capacity and the lowest AAL and λ_C among these models.
- Models TYPE 4 and TYPE 5 show comparable results for most evaluated parameters. The significant difference is observed in TYPE 4, where reinforced ECC composite provides up to 5% higher strength and up to 45% greater ductility compared to the FRP composite used in TYPE 5. Apart from ductility, other results from analyses are nearly identical for both models.
- Model TYPE 6/7 has an identical configuration to TYPE 4, except it utilises double-sided ECC composite strengthening. Double-sided strengthening significantly enhances performance, providing up to 45% higher strength, 15% higher ductility, and resistance to spectral accelerations up to 40% higher compared to TYPE 4. Thus, TYPE 6/7 is identified as the most resilient strengthening system, with ductility comparable to an empty ductile RC frame, along with the lowest AAL and λ_C—up to 35% lower compared to single-sided strengthening (TYPE 4).
- Whenever possible, robust solid clay bricks and commercially available composite materials are recommended for optimal seismic performance enhancement. ECC composites are generally more economical than FRP composites and typically come in easy-to-apply two-component preparations. Applying ECC composites reinforced with galvanized mesh is straightforward, although careful anchoring to the frame and masonry infill walls is necessary. This ECC layer can be integrated into façade layers or applied as an intermediate layer before finishing the wall surfaces.

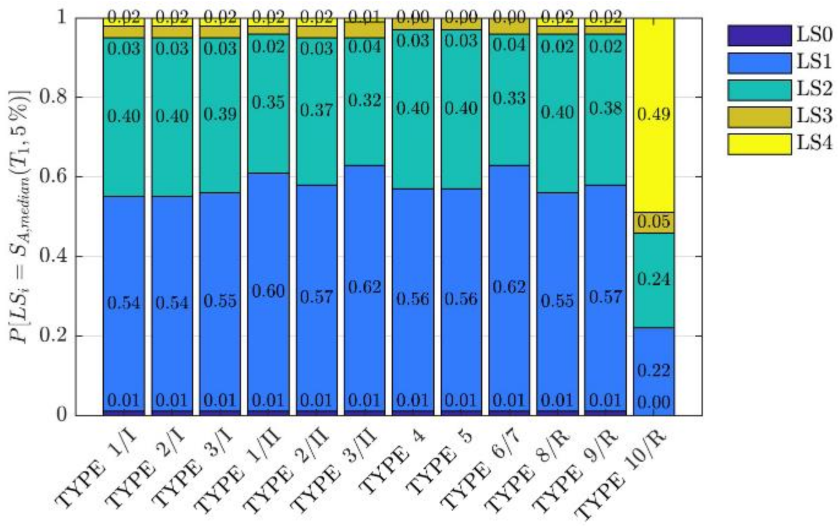

Figure 7. Discrete probability distribution of limit state regions, based on fragility curve analysis.

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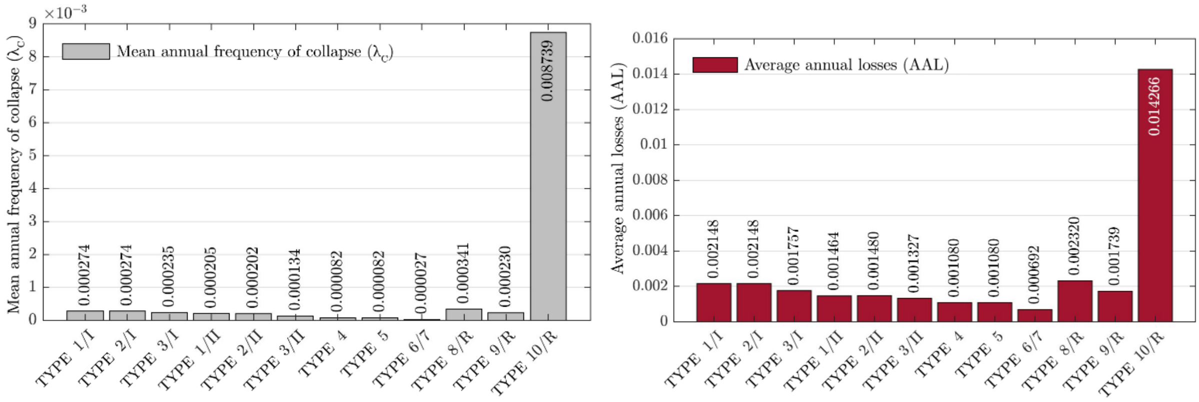

Figure 8. Mean annual frequency of collapse, λ_C (left) and Average annual loss ratio, AAL (right).

6. Conclusions

The results of this study clearly demonstrate the significant benefits of employing simple seismic strengthening techniques, particularly the addition of masonry infill walls, for enhancing the seismic performance of reinforced concrete (RC) frame structures. The detailed numerical analyses highlighted the improved performance of strengthened structures in terms of increased lateral load capacity, ductility, and resilience against seismic-induced damages, compared to bare RC frames.

Empty ductile RC frames (TYPE 10/REF) were identified as notably vulnerable, demonstrating low seismic capacity and significantly higher expected economic losses and collapse risks. Conversely, the introduction of masonry infills substantially improved structural resilience. Specifically, solid brick infills, particularly when combined with vertical confinement and steel dowels (TYPE 3/II), showed a clear advantage over hollow clay block infills. This configuration provided increased strength, reduced expected annual losses, and minimised collapse probabilities, thus indicating a favourable option for seismic retrofitting.

Innovative strengthening approaches involving ECC composites also displayed substantial advantages. Single-sided ECC composite strengthening (TYPE 4) provided moderate improvements in strength and substantial enhancements in ductility compared to FRP composites (TYPE 5). Double-sided ECC strengthening (TYPE 6/7) offered the highest improvement in seismic performance, significantly enhancing both strength and ductility. The findings strongly suggest that ECC composites, due to their cost-effectiveness, ease of application, and substantial performance improvements, should be favoured when practical.

Overall, the application of traditional masonry infill walls combined with targeted composite reinforcement provides a robust, economically viable strategy for enhancing seismic resilience of existing RC frame structures, thus offering a balanced solution between cost-efficiency and seismic performance.

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