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EFFECTIVENESS OF AN INTERNAL SEISMIC RETROFIT STRATEGY ADDRESSED TO LISBON PRE-CODE MASONRY BUILDINGS

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Abstract

The Metropolitan Area of Lisbon is one of the regions with highest exposure and seismic risk within Portugal and Europe, particularly due to a vulnerable building stock built prior to the introduction of any seismic regulations. The recent seismic shocks recorded in 2024 and 2025 have heightened scientific and public concern for severe forthcoming seismic damage and casualties, underscoring the urgent need for tailored mitigation strategies. In such a framework, an internal seismic retrofit strategy tailored to Portuguese masonry typologies is presented in this paper and its effectiveness evaluated.
Given the limited availability of empirical data on earthquake-induced damage to masonry buildings, detailed numerical models were employed to better understand structural seismic responses and to predict likely damage scenarios. Simulations were conducted using the Applied Element Method coupled with Incremental Ground Acceleration analysis, enabling detailed structural modeling with relatively low computational demands.
This study provides updated seismic fragility assessment of pre-code masonry buildings in the Metropolitan Area of Lisbon and evaluates the effectiveness of the strengthening strategy by calculating the damage probability reduction with respect to bare configuration of the models.
The results provide critical insights to inform risk assessments and contribute to the development of targeted retrofit measures, aligned with code seismic hazard and compliant with heritage preservation regulations.

Keywords: Applied Element Method, Metropolitan Area of Lisbon, unreinforced masonry, Incremental Ground Acceleration, fragility curves.

1 INTRODUCTION

Mainland Portugal continues to face considerable seismic vulnerability, with the Metropolitan Area of Lisbon notably impacted by historical events such as the 1755 Lisbon earthquake (Mw=8.5), marking it as one of Europe's highest seismic risk regions [1], [2]. The recent seismic events on August 26, 2024, and February 17, 2025, have renewed attention among scientific and political stakeholders regarding seismic risk assessment and underscored the critical need for effective mitigation strategies.

The unreinforced masonry building stock, which lacks seismic design regulations predating the 1958 RSCCS standard [3], represents the most vulnerable building segment.

Leveraging a comprehensive database of representative pre-code masonry structures from Lisbon [4], this paper develops updated fragility curves consistent with code-compliant seismic assessments [1].

The fragility curves were constructed following an analytical approach, i.e., based on numerical modeling and analyses within the Applied Element Method (AEM). This modeling strategy belong to discontinuous approaches which already proved their effectiveness [5], [6].

Structural models were constructed according to the archetypes A3, B2 and C1 from the building stock in [4]. Incremental Ground Acceleration (IGA) [7] analyses were conducted on detailed 3D structural models to evaluate structural responses under varying seismic hazard conditions. Furthermore, the fragility curves were updated to include an internal seismic retrofit strategy specifically designed for Portuguese masonry typologies, and compliant with the regulations of the Municipality of Lisbon, which forbid any outer façades alterations. The paper thoroughly discusses the improvements gained through retrofitting, highlighting variations in effectiveness related to the archetypes material properties and layouts.

2 MATERIALS AND METHOD

2.1 Archetype models

This paper focuses on the outcomes for three specific masonry archetypes - A3, B2, and C1 (Figure 1) - selected from the five initially modeled (A1, A3, B2, C1, and C3). Archetype B2 serves as the median case, whereas archetype A3 features narrow façades along the X-axis (L_X) and wider façades along the Y-axis (L_Y), and archetype C1 has wide L_X façades and narrow L_Y façades. The dimensions of the evaluated archetypes are as follows: 12.6 × 12.1 m for B2, 17.6 × 8.0 m for C1, and 7.6 × 16.2 m for A3. Buildings with three to five floors were analyzed, each having a consistent inter-story height of 3.0 m.

Wall thicknesses were standardized as follows: 47 cm for main façades, 34 cm for lateral façades, 21 cm for internal load-bearing walls, and 14 cm for partition walls. Masonry mechanical properties adopted from [4] represent the 10th percentile (property set MP5, qualitatively defined as "very scarce") and the 16th percentile (property set MP4, defined as "scarce"). **Table 1** provides a summary of the mechanical properties used in these analyses.

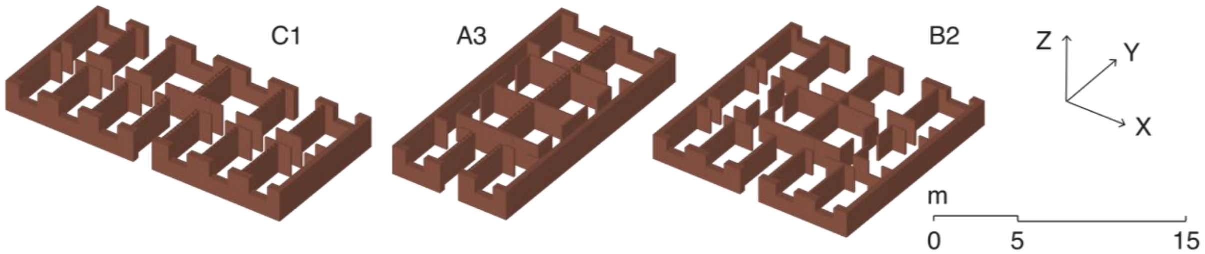

Figure 1. Layout of archetypes C1, A3 and B2.

	E [GPa]		G [GPa]		f_c [MPa]		τ_0 [MPa]	f_t [MPa]	φ [-]	w [kN/m^3]	
	Out	Int	Out	Int	Out	Int				Out	Int
MP4	2.0	1.0	0.85	0.45	2.50	1.25	0.07	0.105	0.8	1.8	1.2
MP5	0.8	0.4	0.34	0.18	1.00	0.5	0.03	0.042	0.8	1.8	1.2

Note: Out – Outer walls, Int – Internal walls, E – Young's modulus, G – shear modulus, f_c – compressive strength, τ_0 – cohesion, f_t – tensile strength, φ – tangent value of friction angle, w – density.

Table 1. Masonry properties set for 10th (MP5) and 16th (MP4) percentiles (from **[8]**).

Floor diaphragms were modeled assuming linear elastic behavior, defined by a Young's modulus of 30 GPa, a shear modulus of 13 GPa, and a thickness of 12 cm. To ensure optimal connectivity and uniform planar displacement, the interfaces between floors and walls were modeled using the same diaphragm properties. Timber lintels classified as C14 were incorporated above openings. Further details can be found in reference [8].
The structural archetypes were modeled using the Applied Element Method (AEM) [9] within the Extreme Loading for Structures software version 9 (ELS v9) [10].

2.2 Retrofit solution

The retrofit solution employed in this study is based on an experimental investigation conducted at the Laboratório Nacional de Engenharia Civil in Lisbon, addressing a masonry typology characteristic of Portugal's unreinforced building stock [11]. The retrofit technique involved in-plane strengthening of masonry walls through jacketing, comprising a 3 cm-thick layer of Natural Hydraulic Lime 3.5 mortar reinforced with embedded fiberglass mesh. This reinforcement layer was anchored to the existing masonry using 7 cm-long plastic fasteners arranged in a 40 × 50 cm grid.

To comply with local preservation regulations from the Municipality of Lisbon which restrict modifications to the exterior appearance of historic buildings, the retrofit layer was applied only on the interior side of the two façades parallel to the X-direction (designated hereafter as 1S). **Figure 2** illustrates the typological layout and its implementation in ELS software. Detailed mechanical properties of the retrofit materials are provided in reference [8].

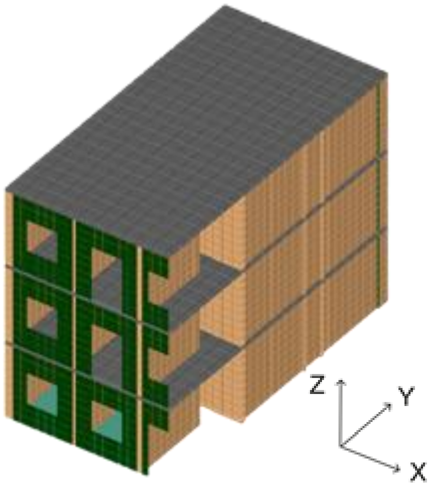

Figure 2. Retrofit layout implemented in ELS (in green the strengthening layer).

2.3 Numerical analysis, construction of fragility curves and code seismic action

Incremental Ground Acceleration analyses were conducted on the selected models to define the corresponding capacity curves in the X-direction for both the bare and strengthened configurations, as detailed in [8].

Based on these results, fragility curves were constructed using a lognormal cumulative distribution function for three Limit States: Damage Limitation (DL), Significant Damage (SD), and Near Collapse (NC), as outlined in Eq. (1). The Peak Ground Acceleration (PGA) was chosen as the Intensity Measure (IM) for this analysis.

$$P(DS_i \mid \mathrm{IM} = \mathrm{PGA}) = \Phi\left[\frac{1}{\beta_T}\cdot \ln\left(\frac{PGA}{PGA_{DS_i}}\right)\right] \tag{1}$$

The demand PGAs were calculated according to [12] in function of the Limit States and Return period (T_R) in years. The resulting values were $PGA_{DL,73y}$=0.08g, $PGA_{SD,308y}$=0.15g, $PGA_{NC,975y}$=0.23g.

3 RESULTS

The fragility curves for the 50th percentile, constructed using PGA as the IM, are presented in **Figure 3**, **Figure 4**, **Figure 5**, for archetypes B2, A3 and C1, respectively.

The effectiveness of the retrofit strategy is evaluated by comparing the curves for the bare and retrofitted configurations in terms of damage probability reduction (DPR).

For the median archetype B2 (**Figure 3**), the results highlight that the strengthening is more effective in reducing the probability of severe damage compared to lighter damage limit states. For the B2-P3 and MP4|MP5 sets, the DPRs are as follows: for Damage Limitation (DL), 21.6%|20%; for Significant Damage (SD), 23.04%|12.3%; and for Near Collapse (NC), 81.7%|53.5%. Additionally, the retrofit strategy appears to perform better with “scarce” properties (MP4) rather than with “very scarce” properties (MP5). Finally, comparing the three- and five-story configurations for P3-P5 and MP5, the DPRs are found to be 20%-19.9% for DL, 12.3%|9.1% for SD, and 53.5%-47.86% for NC.

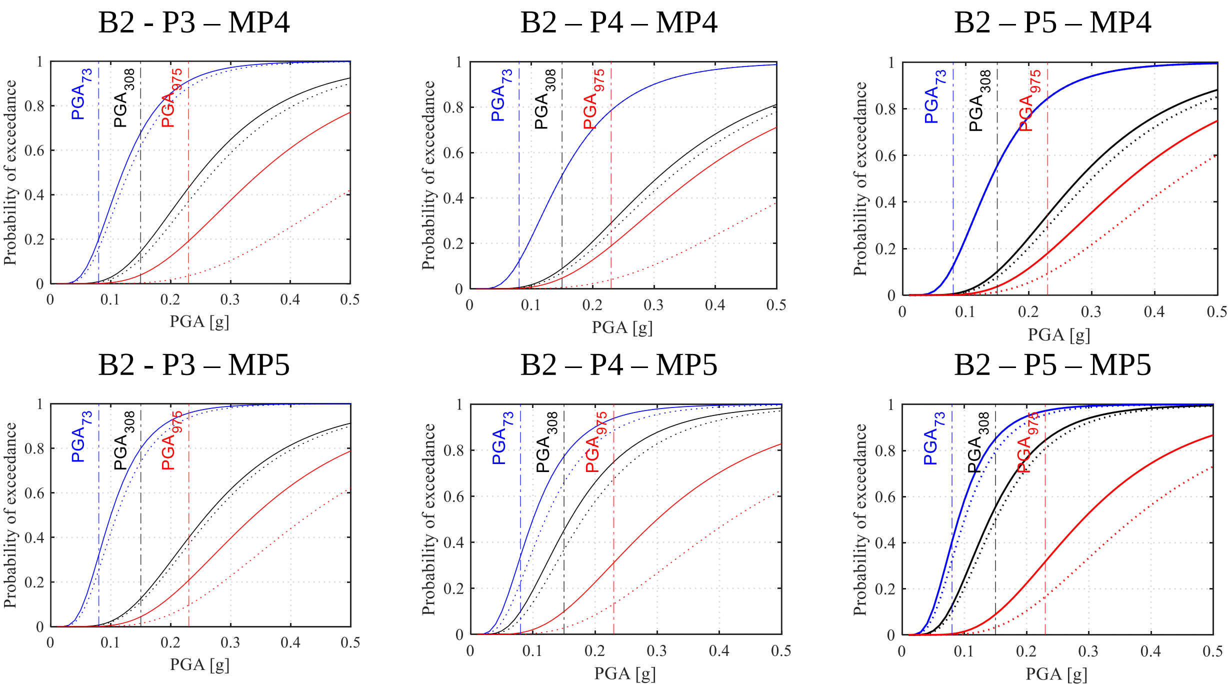

Figure 3. Fragility curves for archetype B2 with bare (continuous line) and 1S retrofit (dotted line) layouts, in function of DL (blue), SD (black) and NC (red) limit states.

The analysis of the results for the median archetype A3 (**Figure 4**) reveals that the retrofit strategy is most effective for the Significant Damage (SD) and Near Collapse (NC) damage states, rather than for Damage Limitation (DL). However, the benefits of the strengthening interventions are less pronounced for archetype A3, as the layout features narrow façades along the X-direction, resulting in a less consistent trend. For the A3-P3 and MP4|MP5 sets, the damage probability reduction (DPR) values are as follows: for DL, 16%|28.8%; for SD, 47.2%|88.9%; and for NC, 91.1%|65.4%.

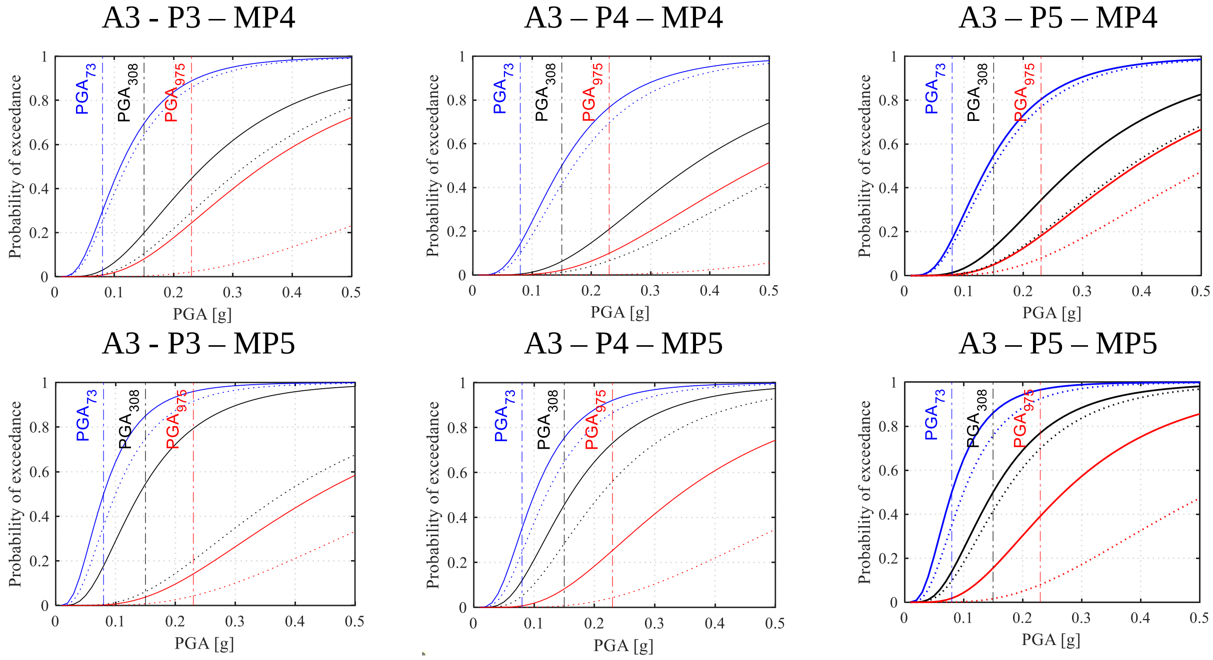

Figure 4. Fragility curves for archetype A3 with bare (continuous line) and 1S retrofit (dotted line) layouts, in function of DL (blue), SD (black) and NC (red) limit states.

The analysis of the results for archetype C1 (**Figure 5**), characterized by wide façades along the X-direction, confirms the findings for archetype B2, showing significant effectiveness in reducing the probability of Near Collapse (NC). For the C1-P3 and MP4|MP5 sets, the damage probability reduction (DPR) values are as follows: for Damage Limitation (DL), 31.45%|30.6%; for Significant Damage (SD), 33%|53.82%; and for NC, 94.5%|61.33%. Finally, when comparing the three- and five-story configurations for P3-P5 and MP5, the DPRs are 30.6%-19.9% for DL, 53.82%-10.5% for SD, and 61.33%-48% for NC. These results further emphasize the reduction in DPR as the number of stories increases.

4 CONCLUSIONS

This paper evaluates the effectiveness of an internal seismic retrofit strategy specifically designed for unreinforced masonry buildings in the MAL region, with a focus on preserving external architectural features. The study investigates the median archetype (B2) along with two boundary cases featuring wider façades along the X-axis (C1) and Y-axis (A3). The analysis considers masonry property sets defined as "scarce" (MP4) and "very scarce" (MP5). Through numerical simulations based on the Applied Element Method combined with Incremental Ground Acceleration analyses, fragility curves were developed, enabling a comprehensive comparison of damage probabilities across three limit states: Damage Limitation (DL), Significant Damage (SD), and Near Collapse (NC).

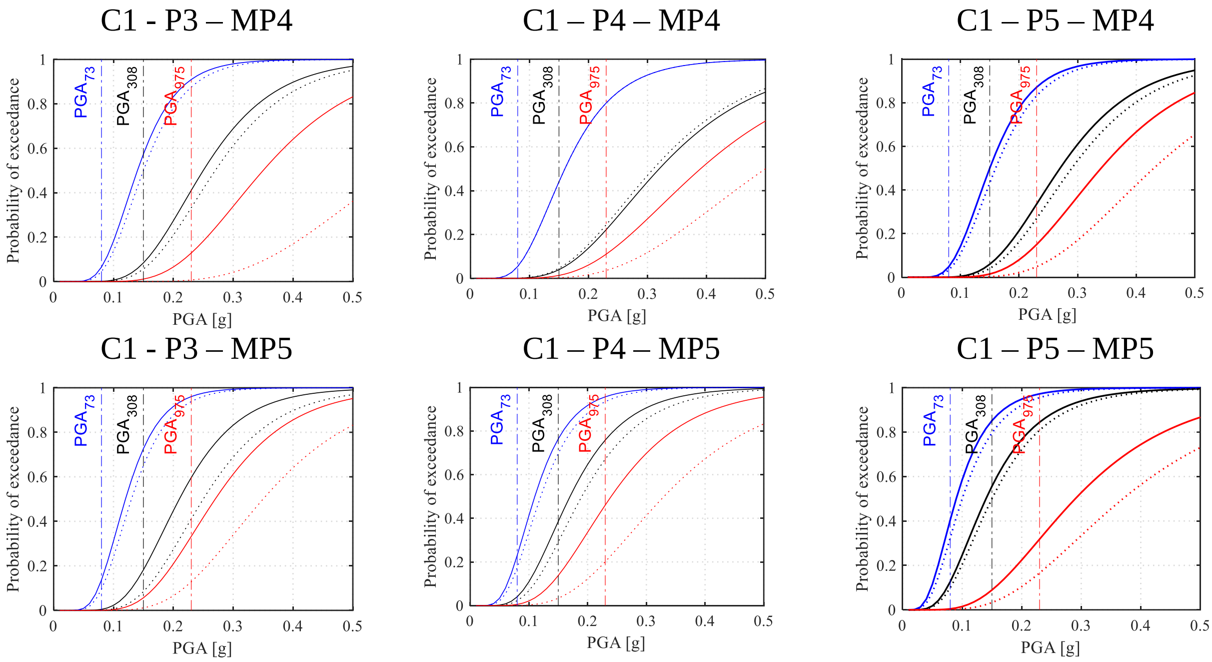

Figure 5. Fragility curves for archetype C1with bare (continuous line) and 1S retrofit (dotted line) layouts, in function of DL (blue), SD (black) and NC (red) limit states.

The results reveal that while the internal strengthening technique provides a moderate improvement at the DL state, significant benefits are observed at the SD and especially at the NC limit states. For example, in three-story configurations, aggregated data for MP4 and MP5 show reductions in damage probability ranging from 9.1% to 30% for DL, 10.5% to 88.9% for SD, and between 53.5% and 94.5% for NC. However, the effectiveness of the strengthening intervention decreases as the number of stories increases. The adoption of alternative integrated retrofit strategies inclusive of energy-reduction performances, such as the *Nested Building* [13], [14], will be assessed in future studies.

The fragility curves presented can be incorporated into urban-scale risk assessments to update risk maps and inform the development of mitigation strategies and resilience enhancement policies.

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