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Research Article

Seismic Performance and Retrofit-Based Guidelines for DS-4 Unreinforced Masonry Buildings Evidence from Eight Real Case Studies

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Abstract

Unreinforced masonry (URM) buildings constitute a substantial share of the existing building stock in many seismic regions and have repeatedly demonstrated poor seismic performance during recent earthquakes. After strong ground motions, a significant portion of these structures are classified as severely damaged (DS-4), a condition that typically requires detailed structural assessment and retrofit in order to restore acceptable safety levels. Although the seismic behaviour of URM buildings has been widely investigated, practical performance ranges derived from real post-earthquake case studies remain limited, particularly for buildings already affected by severe damage. This study presents a seismic performance assessment of eight real URM buildings classified as DS-4 following the 26 November 2019 Albania earthquake. All buildings were subjected to detailed on-site inspections, material characterization through laboratory testing, numerical modelling, and nonlinear static (pushover) analysis. The seismic response was evaluated both in the damaged (existing) condition and after the implementation of retrofit interventions designed in accordance with Eurocode 8 – Part 3. A macro-element modelling approach was adopted to ensure consistency in the evaluation of global capacity, drift limits, and ductility across the dataset. The results provide quantitative insight into the typical seismic capacity of severely damaged URM buildings and demonstrate the level of performance improvement achievable through commonly adopted retrofit strategies. Based on the synthesis of the eight case studies, realistic seismic performance ranges for DS-4 URM buildings are identified, together with target values for retrofitted configurations. The findings are intended to support engineers involved in post-earthquake assessment and retrofit design by providing reference benchmarks grounded in real building behaviour.

Keywords: Unreinforced Masonry; Seismic Assessment; DS-4 Damage State; Pushover Analysis; Structural Retrofit, Performance-based Evaluation, Eurocode 8.

INTRODUCTION

Unreinforced masonry (URM) buildings represent a significant portion of the residential and public building stock in many seismic regions, particularly in Southern and

Eastern Europe. The majority of these structures were constructed before the introduction of modern seismic design provisions and were therefore not conceived to resist earthquake actions [1-3]. As a result, past seismic events have repeatedly shown that URM buildings are highly vulnerable, often suffering extensive damage or partial collapse even under moderate seismic excitation.

The earthquake that struck Albania on 26 November 2019 once again highlighted this structural vulnerability [4, 5]. A large number of low- and mid-rise masonry buildings experienced severe damage and were classified as DS-4 according to the Post-Disaster Needs Assessment (PDNA) methodology. Buildings in this damage state typically exhibit widespread cracking of load-bearing walls, degradation of shear resistance, and a substantial reduction in global stiffness and strength [6]. In practical terms, DS-4 buildings cannot be considered safe for continued use without detailed seismic assessment and, in most cases, structural retrofit.

A considerable body of literature has investigated the seismic behaviour of URM buildings using experimental testing, analytical formulations, and numerical simulations. Macro-element and equivalent-frame modelling approaches, in particular, have become widely adopted tools for the assessment of existing masonry structures. However, many available studies focus on idealized or undamaged configurations, while fewer contributions are based on comprehensive datasets obtained from real buildings that have already experienced severe earthquake damage. Consequently, engineers often lack reliable reference ranges describing the expected seismic performance of DS-4 URM buildings, as well as realistic performance targets that can be achieved through retrofit interventions.

Within this context, the present study aims to contribute practical evidence derived from real post-earthquake case studies. Eight URM buildings classified as DS-4 after the 2019 Albania earthquake were selected and analysed using a consistent assessment framework. For each building, seismic performance was evaluated both in the damaged condition and after retrofit measures designed in accordance with Eurocode 8 – Part 3 [7]. Nonlinear static (pushover) analysis was employed to quantify global capacity, drift limits, and ductility demand, allowing direct comparison between pre- and post-intervention behaviour.

Rather than proposing new modelling techniques, the objective of this work is to synthesize the observed seismic response of severely damaged URM buildings and to identify realistic performance ranges grounded in real structural behaviour. Based on the complete dataset, the paper proposes indicative seismic performance benchmarks for DS-4 URM buildings and corresponding target values after retrofit. These results are intended to support post-earthquake decision-making and retrofit design for masonry buildings with similar construction characteristics and damage levels [8-10].

RESEARCH GAPS AND CONTRIBUTIONS

Despite the extensive body of literature dedicated to the seismic assessment of unreinforced masonry (URM) buildings, several aspects related to post-earthquake performance and retrofit effectiveness remain insufficiently documented. Many existing studies focus on idealized building configurations or on undamaged structures assessed under design-level seismic actions. By contrast, fewer investigations address buildings that have already experienced severe earthquake damage and are subsequently classified in advanced damage states, such as DS-4.

Previous research has established modelling strategies for URM buildings, including equivalent-frame and macro-element approaches, and has provided general performance limits for masonry structures [11-14]. However, these studies often rely on assumed material properties, simplified damage representations, or hypothetical retrofit scenarios. As a result, there is limited consensus on the expected seismic capacity of severely damaged URM buildings in their post-earthquake condition, as well as on the realistic level of performance improvement that can be achieved through commonly applied retrofit interventions [15-19].

In particular, existing guidelines and assessment frameworks provide limited quantitative benchmarks derived from real buildings subjected to detailed inspection, material testing, and retrofit verification [20-22]. This gap becomes critical in post-earthquake contexts, where engineers are required to make rapid yet reliable decisions regarding usability, strengthening needs, and target performance levels under constrained information and time conditions.

Within this context, the present study addresses the following research questions:

- *RQ1*: What are the characteristic seismic performance ranges (strength, drift capacity, and ductility) of URM buildings classified as DS-4 based on real post-earthquake case studies?
- *RQ2*: To what extent can commonly adopted retrofit strategies improve the global seismic performance of DS-4 URM buildings when designed in accordance with Eurocode 8 – Part 3?

Based on these questions, the following working hypotheses are examined through the analysis of eight real case studies:

- *H1:* URM buildings classified as DS-4 exhibit low normalized base shear capacity and limited deformation capacity, consistent with a predominantly shear-governed and brittle seismic response.
- *H2:* Retrofit interventions targeting global connectivity, diaphragm action, and confinement of masonry walls can significantly increase both lateral strength and deformation capacity, leading to a transition towards a more controlled and ductile global response.

The main contribution of this study lies in the synthesis of seismic performance data obtained from real URM buildings that were severely damaged during a recent earthquake and subsequently assessed and retrofitted using a consistent methodology. Rather than proposing new analytical models or retrofit techniques, the paper provides empirically grounded performance ranges and retrofit target values that can be used as reference benchmarks in similar seismic contexts.

Compared to existing state-of-the-art studies, the novelty of the work resides in the exclusive focus on DS-4 buildings, the consistency of the assessment and retrofit framework across all case studies, and the direct comparison between pre- and post-retrofit seismic performance. The results therefore complement existing analytical and experimental research by offering practical performance-oriented guidance derived from real building behaviour.

DESCRIPTION OF THE BUILDING DATASET

General Characteristics of the URM building stock

The building dataset analysed in this study consists of eight unreinforced masonry (URM) buildings located in different areas affected by the 26 November 2019 Albania earthquake. The selected buildings are representative of a large portion of the Albanian masonry building stock, particularly residential and public structures constructed prior to the introduction of modern seismic design provisions. All buildings included in the dataset are low- to mid-rise structures, with two or three storeys above ground level, and exhibit relatively regular plan configurations. Load-bearing masonry walls constitute the primary vertical and lateral load-resisting system. No building was originally designed according to seismic codes, and seismic detailing is generally absent or minimal, as commonly observed in pre-code masonry construction in the region.

The masonry typologies vary slightly among the buildings but remain within a typical range for Albanian practice. Clay brick masonry and silicate brick masonry are the dominant materials, bonded with lime-based or low-strength cementitious mortars. These construction characteristics are consistent with those documented in post-earthquake surveys carried out after the 2019 event and reflect widespread construction practices in Albania and other Mediterranean seismic regions.

Floor systems differ across the dataset and include flexible diaphragms as well as partially stiffened horizontal elements. In several cases, floor-to-wall connections were found to be inadequate, leading to limited diaphragm action and unfavourable global seismic behaviour. This variability in diaphragm stiffness plays an important role in the observed seismic response and is therefore a relevant aspect of the dataset.

Figure 1 presents façade views of the eight buildings included in the study. Although none of the buildings experienced global collapse, all were classified as severely damaged (DS-4) following post-earthquake inspection, indicating a substantial reduction in structural capacity and the need for retrofit intervention prior to re-occupancy.

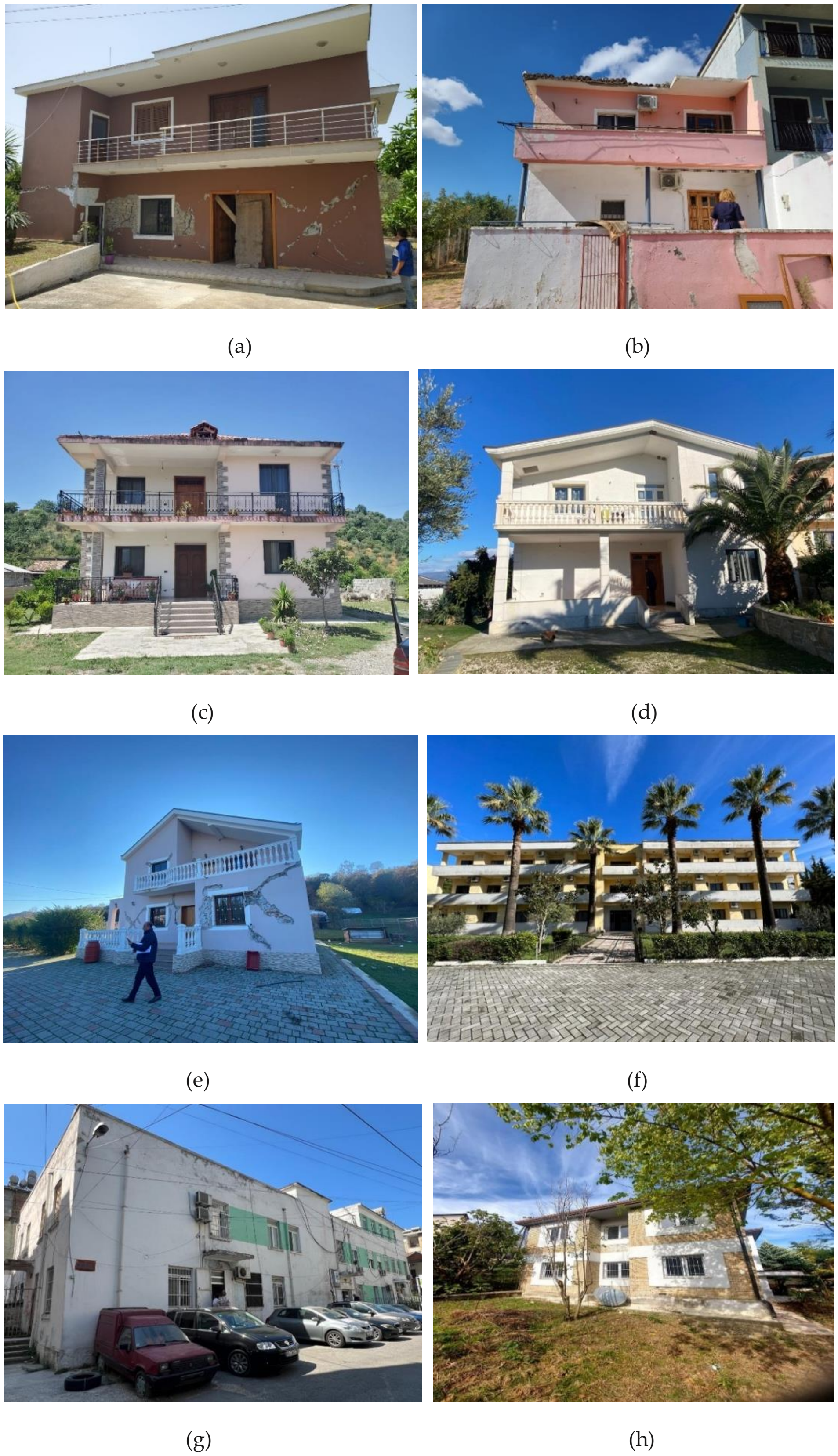


Figure 1. Building façade photos: a,b (first row); c,d (second row); e,f (third row) g,h (last row)

Damage Classification and Available Investigations

Damage classification for all buildings was performed in accordance with the Post-Disaster Needs Assessment (PDNA) methodology adopted after the 2019 Albania earthquake. The DS-4 damage state corresponds to severe structural damage, characterized by extensive cracking of load-bearing walls, significant degradation of shear resistance, and local loss of structural integrity.

On-site inspections revealed recurring damage patterns across the analysed buildings. The most common mechanisms include diagonal shear cracking of masonry walls, crack concentration around openings, and damage at wall intersections. In several cases, cracks extended through the full wall thickness, indicating a substantial reduction in effective shear capacity. Local crushing of masonry units and mortar deterioration were also frequently observed.

Particular vulnerability was noted in buildings with flexible or poorly connected diaphragms. Inadequate wall-to-floor connections contributed to non-uniform force distribution and increased susceptibility to both in-plane and out-of-plane failure mechanisms. While global collapse was not observed, the severity and spatial distribution of damage justified the DS-4 classification for all buildings in the dataset.

For each case study, a comprehensive set of technical documentation was available and used in the analysis. This included:

- detailed visual inspections supported by photographic documentation;
- geometric surveys and architectural drawings;
- identification of structural deficiencies and dominant damage mechanisms;
- material characterization based on in-situ sampling and laboratory testing.

The availability of consistent and relatively complete investigation data for all eight buildings allowed the development of reliable numerical models reflecting the actual post-earthquake condition of the structures.

Material Characterization

On-site inspections revealed recurring damage patterns across the analysed buildings. The most common mechanisms include diagonal shear cracking of masonry walls, crack concentration around openings, and damage at wall intersections. In several cases, cracks extended through the full wall thickness, indicating a substantial reduction in effective shear capacity. Local crushing of masonry units and mortar deterioration were also frequently observed.

Table 1 summarizes the compressive strength values obtained for bricks, mortar, and masonry assemblages for all buildings in the dataset. Brick compressive strengths are generally in the range of 3–5 MPa, while mortar compressive strengths typically vary between 1.0 and 2.5 MPa. The resulting masonry compressive strength values remain well below those recommended by Eurocode 6 for structural masonry in seismic regions.

The experimentally obtained values are consistent with the observed damage patterns and provide quantitative justification for the limited seismic capacity identified during post-earthquake inspections. These material properties were subsequently adopted as input parameters for numerical modelling, with conservative assumptions applied where necessary to account for damage-induced degradation in accordance with Eurocode 8 – Part 3.

Table 1. Summary of laboratory test results for masonry materials of the analysed URM buildings.

Building ID	Material properties	Brick compressive strength f_b	Mortar compressive strength f_m	Masonry compressive strength f_k
Building 1	Clay bricks, lime mortar	4–5 MPa	1.5 – 2.5 MPa	1.75-2.25 MPa
Building 2	Clay bricks, lime mortar	4–5 MPa	2 – 2.5 MPa	2 – 2.5 MPa
Building 3	Silicate bricks, cement mortar	4–5 MPa	1.5 – 2.5 MPa	1.75-2.25 MPa
Building 4	Clay bricks, cement mortar	3–4 MPa	1– 1.5 MPa	1.5 – 2 MPa
Building 5	Clay bricks, lime mortar	4–5 MPa	1.5 – 2.5 MPa	1.75-2.25 MPa
Building 6	Silicate bricks, cement mortar	3–4 MPa	2 – 2.5 MPa	1.75-2.25 MPa
Building 7	Silicate bricks, lime mortar	4–5 MPa	2 – 2.5 MPa	2 – 2.5 MPa
Building 8	Clay bricks, cement mortar	4–5 MPa	1– 1.5 MPa	1.5 – 2 MPa

It should be noted that, although variability exists among individual buildings, the overall material strength ranges are relatively narrow, supporting the representativeness of the dataset for the considered building typology.

Overview of Numerical Modelling and Retrofit Documentation

All buildings were modelled using a macro-element approach implemented in specialized masonry analysis software. This modelling strategy enables an efficient yet accurate representation of nonlinear masonry behaviour, including shear, flexural, and combined failure mechanisms at the wall level. The adopted approach is particularly suitable for the assessment of existing URM buildings, where global performance is strongly influenced by localized damage mechanisms. For each building, two numerical models were developed:

- an existing-condition model, reflecting the post-earthquake damaged state;
- a retrofitted-condition model, incorporating the strengthening interventions.

Retrofit projects were designed in accordance with Eurocode 8 – Part 3, aiming to improve both lateral strength and deformation capacity while maintaining compatibility with the existing masonry structure. Although retrofit strategies varied among buildings, they generally included combinations of horizontal ring beams, diaphragm stiffening, local wall strengthening, and, where necessary, foundation-level interventions.

The availability of consistent modelling and retrofit documentation for all eight buildings enables a direct comparison between pre- and post-intervention seismic performance and forms the basis for the synthesis and guideline development presented in the following sections.

SEISMIC ASSESSMENT OF EXISTING URM BUILDINGS (DS-4)

On-Site Investigation, Damage Assessment, and Material Characterization

A detailed on-site investigation was carried out for all eight unreinforced masonry (URM) buildings included in the study, with the aim of identifying structural deficiencies, damage distribution, and dominant failure mechanisms induced by the 26 November 2019 earthquake. Visual inspections were systematically performed and supported by extensive photographic documentation, geometric surveys, and material sampling.

Figure 2. Building 7 Degradation and severe damage on structural walls and beams

The observed damage patterns were largely consistent across the analysed buildings and are representative of the DS-4 damage state as defined by the PDNA methodology. Extensive diagonal cracking was frequently observed in load-bearing masonry walls, indicating the activation of in-plane shear failure mechanisms (Figure 2). In several cases, cracks propagated through the full thickness of the walls, leading to a significant reduction in effective shear resistance. Additional damage features included localized crushing of masonry units, mortar disintegration, and crack concentration around openings and wall intersections (Figure 3). These mechanisms reflect the limited tensile and shear capacity of the masonry assemblages and the absence of seismic detailing typical of pre-code construction.

Buildings characterized by flexible or insufficiently connected diaphragms exhibited particularly unfavourable damage distributions. Inadequate wall-to-floor connections limited force redistribution among walls and increased vulnerability to both in-plane and out-of-plane mechanisms. Although none of the buildings experienced global collapse, the severity and spatial extent of damage resulted in a substantial reduction of lateral stiffness and load-bearing capacity, justifying their classification as DS-4.

Figure 3. Building 5 Shear cracks and severe damage on URM walls

Material characterization was conducted through laboratory testing of masonry units and mortar samples extracted during the inspections. The experimental results confirmed the generally low mechanical properties of the existing masonry, consistent with pre-code construction practice. These values provided quantitative support to the observed damage mechanisms and were subsequently adopted as input parameters for numerical modelling.

Numerical Modelling and Pushover Analysis Methodology

The seismic assessment of the existing buildings was performed using nonlinear static (pushover) analysis. A macro-element modelling approach was adopted, allowing the representation of masonry walls as assemblages of nonlinear elements capable of reproducing shear, flexural, and combined failure mechanisms under increasing lateral demand. Material properties assigned to the numerical models were defined on the basis of the laboratory test results summarized in Table 1. Where required, conservative assumptions were introduced in accordance with Eurocode 8 – Part 3 to reflect the degraded post-earthquake condition of the structures. Existing damage was implicitly considered through reduced stiffness and strength parameters, rather than explicit modelling of individual cracks.

Pushover analyses were carried out by applying monotonically increasing lateral forces in the principal horizontal directions of each building. Load patterns proportional to the mass distribution were adopted, and analyses were continued until near-collapse conditions were reached. Near-collapse was identified by either a marked reduction in global load-carrying capacity or the attainment of excessive roof displacement.

Seismic performance was evaluated in terms of global response parameters, including normalized base shear (Vb/W), roof displacement, interstorey drift ratios, and global ductility. Performance levels corresponding to Damage Limitation (DL), Significant Damage (SD), and Near Collapse (NC) were identified in accordance with the criteria defined in Eurocode 8 – Part 3.

Seismic Performance of Existing URM Buildings

The results of the pushover analyses for the existing (post-earthquake) condition of the eight URM buildings are summarized in Table 2. The numerical outcomes consistently indicate limited seismic capacity, confirming the severe vulnerability associated with the DS-4 damage state.

Table 2. Pushover analysis results for the existing condition of the analysed URM buildings (DS-4)

Building ID	Vb/W Base shear force/ weight	d DL displacement /height DL	d SD displacement/height SD	d NC displacement /height SD	μ ductility
Building 1 x	15,43%	0,095%	0,206%	0,333%	1,77692
Building 1 y	11,47%	0,095%	0,190%	0,302%	1,60769
Building 2 x	16,77%	0,095%	0,175%	0,365%	1,78169
Building 2 y	15,57%	0,095%	0,159%	0,317%	1,5493
Building 3 x	14,85%	0,095%	0,206%	0,333%	1,925
Building 3 y	14,52%	0,095%	0,190%	0,302%	1,74167
Building 4 x	14,03%	0,095%	0,206%	0,333%	1,925
Building 4 y	12,76%	0,095%	0,175%	0,317%	1,83333
Building 5 x	11,79%	0,079%	0,175%	0,222%	1,64706
Building 5 y	9,09%	0,079%	0,143%	0,190%	1,41177
Building 6 x	12,30%	0,091%	0,190%	0,299%	1,86891
Building 6 y	9,15%	0,091%	0,156%	0,251%	1,56639
Building 7 x	11,93%	0,097%	0,191%	0,276%	1,67974
Building 7 y	9,18%	0,097%	0,156%	0,249%	1,51634
Building 8 x	12,62%	0,086%	0,203%	0,286%	1,7581
Building 8 y	12,28%	0,086%	0,145%	0,263%	1,6193

Normalized base shear capacities (Vb/W) are low across the dataset, reflecting the limited shear resistance of the masonry walls and the absence of effective seismic detailing. Drift capacities associated with the DL and SD performance levels are relatively small, while near-collapse drift limits indicate a narrow deformation margin between severe damage and potential collapse. Global ductility values are correspondingly low, typically remaining below 2.0. This behaviour is indicative of a predominantly brittle seismic response governed by shear-dominated failure mechanisms. The influence of poor diaphragm action and insufficient wall-to-floor connections, previously identified during on-site inspections, is clearly reflected in the global response parameters.

Table 3. Statistical synthesis of seismic performance parameters for the existing URM buildings.

Parameter	Minimum	Maximum	Mean	Standard Deviation
Vb/W	9%	17%	12,75%	~2,4%
d DL	0,079%	0,097%	0,092%	~0,006%
d SD	0,143%	0,206%	0,179%	~0,020%
d NC	0,19%	0,365%	0,290%	~0,045%
μ	1,41	1,93	1,70	~0,015

Figure 4 presents the capacity curves obtained for all buildings in both principal directions. Despite some variability related to geometry, construction details, and diaphragm stiffness, the overall trends are consistent across the dataset. The statistical synthesis reported in Table 3 further highlights the limited strength and deformation capacity characterizing URM buildings in the DS-4 damage state.

These results establish a quantitative baseline for the assessment of severely damaged URM buildings and provide a reference framework against which the effectiveness of retrofit interventions can be evaluated in the following sections.

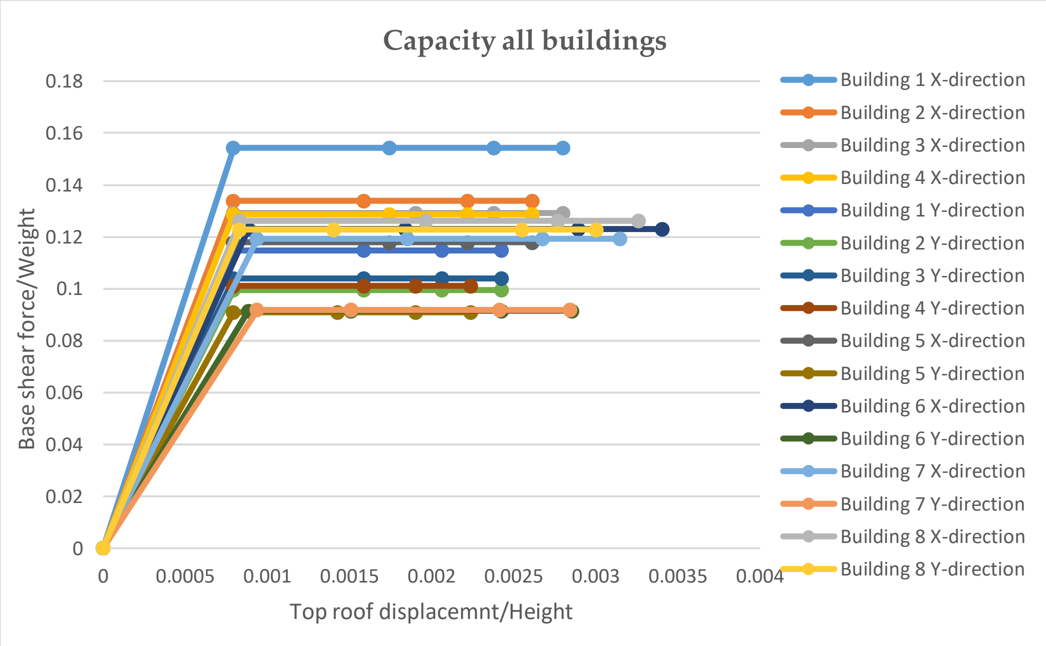


Figure 4. Capacity curves of all buildings in both directions

RETROFIT STRATEGIES AND SEISMIC PERFORMANCE IMPROVEMENT

Overview of adopted retrofit techniques

The retrofit solutions adopted for the analysed unreinforced masonry (URM) buildings follow a consistent, typology-oriented strengthening philosophy. Given the DS-4 damage state and the recurrent structural deficiencies identified during the assessment phase, the retrofit design focused on improving global structural behaviour rather than addressing isolated local damage.

The selected interventions were intended to enhance lateral strength, deformation capacity, and structural connectivity, while remaining compatible with the existing masonry fabric. Although specific details vary among individual buildings, the retrofit strategies share a common conceptual framework, enabling a coherent comparison of their effectiveness across the dataset.

Four main retrofit components were systematically adopted:

- ***Introduction of perimeter reinforced concrete columns.*** Reinforced concrete (RC) columns were added along the perimeter of the buildings, typically at corners and at the ends of long unbraced masonry walls, see Figure 5. These elements act as vertical confinement members, improving continuity between foundations, walls, and floor systems. Their presence significantly increases global lateral resistance and reduces the likelihood of brittle shear failures and corner separations.

- ***Local strengthening and rehabilitation of masonry walls.*** Where walls exhibited extensive cracking or material degradation, local strengthening measures were implemented. These included repair of damaged masonry, partial reconstruction of severely deteriorated panels, and, where required, thin reinforced concrete jacketing, see Figure 6. The objective of these interventions was to restore wall integrity and shear capacity while limiting stiffness irregularities within the structural system.
- ***Diaphragm stiffening and restoration of box behaviour.*** A major deficiency identified during the assessment phase was the lack of effective diaphragm action. Retrofit interventions therefore targeted the stiffening of existing floor systems and the improvement of wall-to-floor connections. Reinforced concrete slabs, steel elements, and continuous ring beams were introduced to enhance in-plane rigidity, promote force redistribution, and ensure box-type behaviour under seismic loading.
- ***Strengthening of wall-to-slab and foundation connections.*** To ensure effective transfer of seismic forces and prevent separation between structural components, specific measures were adopted at floor and foundation levels. These included the installation of steel anchors and dowels, as well as local foundation strengthening to accommodate newly introduced RC elements. These measures contribute to global stability and reliable interaction between existing and added structural components.

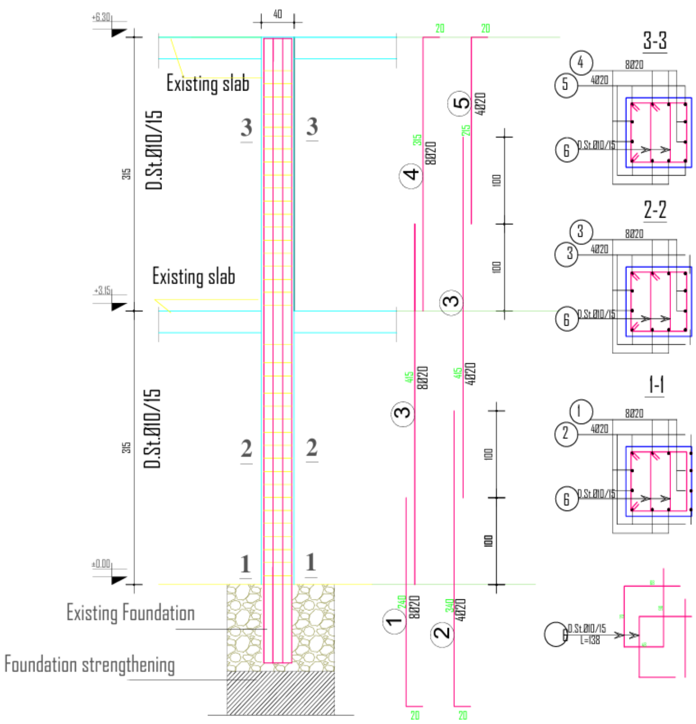


Figure 5. Added perimeter reinforcing concrete columns implemented on building 7

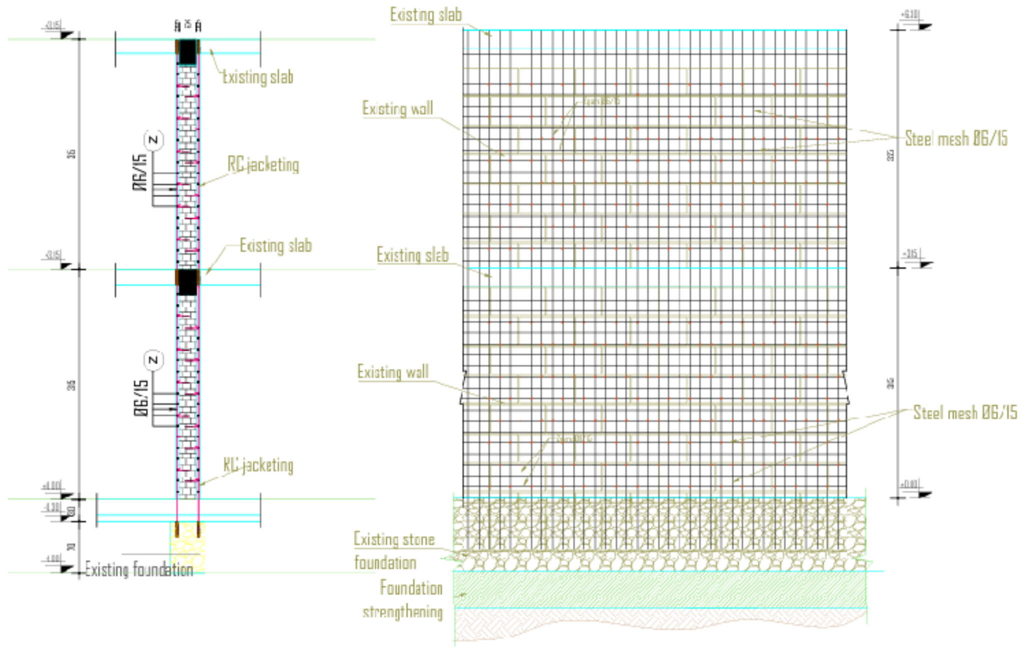


Figure 6. Local wall repair with RC jacketing adopted in Building 7

Overall, the adopted retrofit strategy aims to transform the original URM buildings from systems composed of weakly connected masonry walls into integrated structural units with improved strength, ductility, and deformation capacity. The reliance on a limited number of repeatable interventions makes this approach particularly suitable for application to larger URM building stocks with similar characteristics.

Detailed Retrofit Design for Building 7

To illustrate the adopted retrofit framework and its practical implementation, building 7 is presented as a representative case study. This building exhibits typical characteristics and deficiencies observed across the analysed dataset and therefore provides a meaningful example of the applied strengthening strategy. The seismic assessment of the existing condition of Building 7 revealed several critical vulnerabilities. These included limited in-plane shear capacity of masonry walls, insufficient wall-to-floor connections, and inadequate diaphragm stiffness. As a result, the building exhibited non-uniform force distribution and a predominantly shear-governed seismic response.

Observed damage patterns included diagonal cracking of load-bearing walls and material degradation concentrated around openings and wall intersections. Based on these findings, the retrofit design was developed with the following objectives:

- increase global lateral strength and stiffness;
- improve deformation capacity and reduce brittle failure modes;
- ensure effective diaphragm action and box-type behaviour;
- enhance connectivity among walls, floors, and foundations.

The retrofit solution for Building 7 follows the general strategy outlined in Figures 7 and 8 which consists of coordinated interventions designed to act as an integrated system.

Perimeter RC columns were introduced at building corners and along selected masonry walls to provide vertical confinement and enhance lateral resistance. Local strengthening measures were applied to damaged masonry panels to restore shear capacity and improve wall integrity. Diaphragm stiffening was achieved through the introduction of reinforced concrete elements and continuous ring beams at floor levels, ensuring effective force redistribution among walls. Wall-to-floor and wall-to-foundation connections were strengthened through mechanical anchorage and local foundation interventions, improving overall structural continuity.

These measures were designed to work collectively rather than independently, ensuring that improvements in strength and stiffness are accompanied by enhanced deformation capacity and controlled global behaviour.

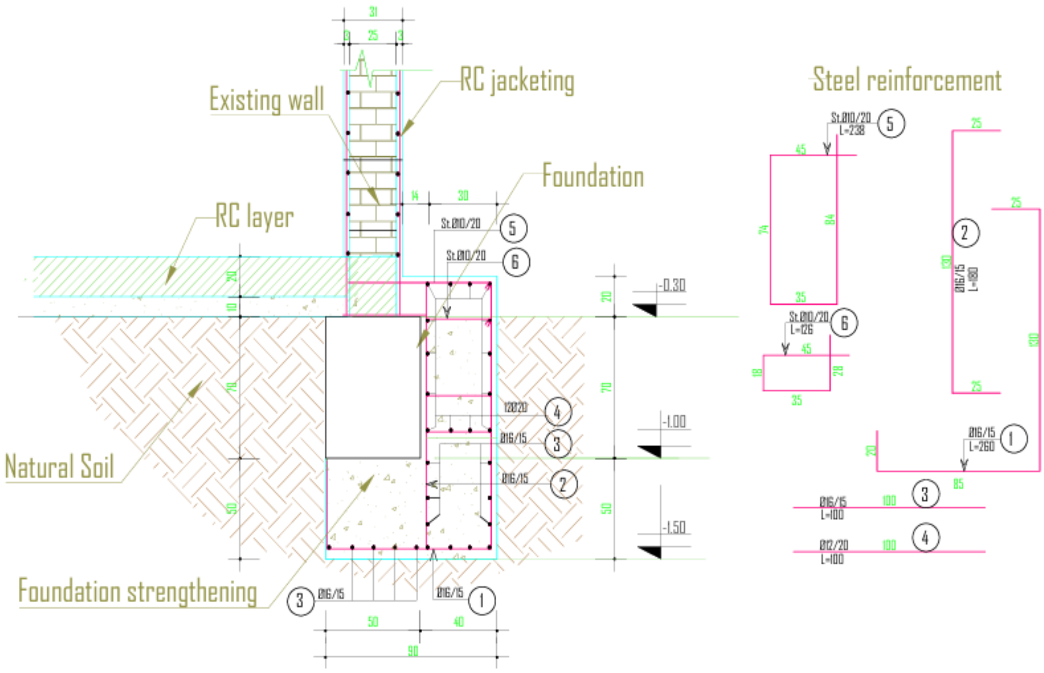
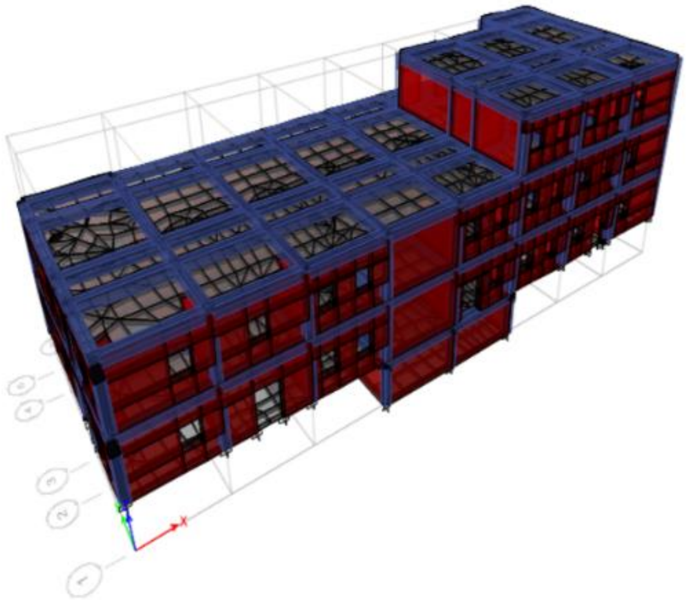


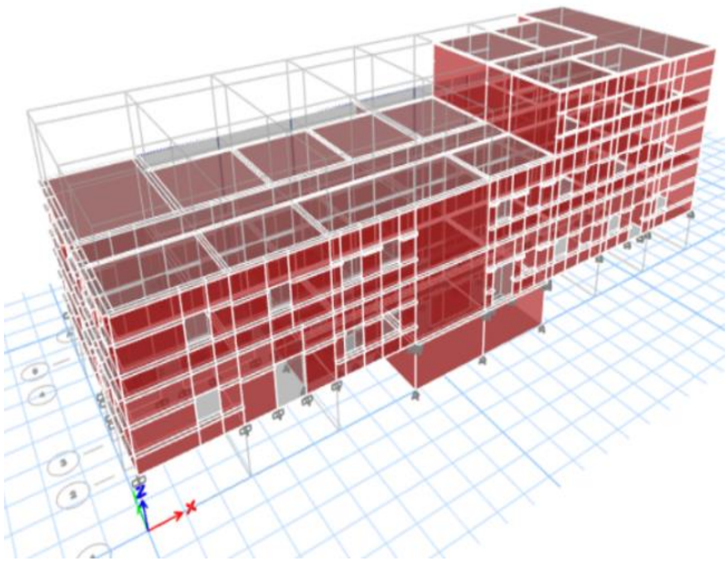
Figure 7. Foundation strengthening details implemented on building 7

Numerical Modelling of the Retrofitted Configuration

The numerical model of Building 7 was updated to explicitly include all retrofit elements, maintaining consistency with the modelling assumptions adopted for the existing condition. Reinforced concrete columns, diaphragm stiffening elements, and ring beams were modelled as integrated components interacting with the masonry macro-elements. The retrofitted model was subjected to nonlinear static (pushover) analysis using the same loading patterns and performance criteria adopted for the existing-condition analysis. This allowed a direct comparison between the pre- and post-retrofit seismic response of the building. The resulting capacity curves show a clear increase in both lateral strength and deformation capacity, confirming the effectiveness of the adopted retrofit strategy. These results are discussed in detail in the following section, where the seismic performance of all retrofitted buildings is quantitatively evaluated.



(a)



(b)

Figure 8. Building 7: (a)-model before retrofit and (b)-after retrofit

Seismic Performance after Retrofit Interventions

The seismic performance of the retrofitted URM buildings was evaluated through nonlinear static analyses, and the results are summarized in Table 4. Compared to the existing condition, all buildings exhibit a clear and consistent improvement in global seismic response.

Table 4. Pushover analysis results for the retrofitted condition of the analysed URM buildings

Building ID	**Vb/W Force/ weight**	**d DL displ/height**	**d SD displ/height**	**d NC displ/height**	**μ ductility**
Building 1 x	25,05%	0,159%	0,397%	0,794%	3,233
Building 1 y	23,94%	0,159%	0,413%	0,746%	3,041
Building 2 x	27,40%	0,159%	0,413%	0,825%	3,178
Building 2 y	25,52%	0,159%	0,397%	0,794%	3,056
Building 3 x	27,09%	0,159%	0,349%	0,778%	3,170
Building 3 y	25,93%	0,159%	0,317%	0,746%	3,041
Building 4 x	29,17%	0,159%	0,460%	0,841%	3,331
Building 4 y	27,71%	0,159%	0,429%	0,825%	3,269
Building 5 x	22,96%	0,127%	0,333%	0,651%	3,203
Building 5 y	21,29%	0,127%	0,317%	0,619%	2,5
Building 6 x	22,98%	0,108%	0,344%	0,581%	3,462
Building 6 y	20,50%	0,108%	0,323%	0,570%	3,3974
Building 7 x	24,73%	0,108%	0,312%	0,548%	3,1875
Building 7 y	22,86%	0,108%	0,301%	0,516%	3
Building 8 x	27,04%	0,108%	0,323%	0,591%	3,2738
Building 8 y	25,73%	0,108%	0,312%	0,548%	3,0357

Normalized base shear ratios (Vb/W) increase significantly after retrofit, indicating a substantial enhancement of lateral strength. This improvement is primarily associated with the introduction of perimeter RC elements, improved diaphragm action, and enhanced connectivity among structural components.

Drift capacities corresponding to the Damage Limitation (DL), Significant Damage (SD), and Near Collapse (NC) performance levels also increase markedly. The observed increase in near-collapse drift limits reflects a wider deformation capacity and a reduced tendency towards brittle failure mechanisms.

Global ductility values further confirm the effectiveness of the adopted retrofit strategies. In all analysed cases, ductility values after retrofit exceed those of the existing condition by a substantial margin, indicating an improved ability of the structural system to dissipate seismic energy and sustain inelastic deformations without abrupt loss of capacity.

The statistical synthesis presented in Table 5 highlights the consistency of these improvements across the dataset. Although variability exists among individual buildings, the overall trends demonstrate that the adopted retrofit framework is effective in upgrading DS-4 URM buildings to significantly improved seismic performance levels.

Table 5. Statistical synthesis of seismic performance parameters for the retrofitted URM buildings.

Parameter	Min	Max	Mean	Standard Deviation
V_b/W	20,5%	29,17%	25,3%	~2,5%
d DL	0,108%	0,159%	0,134%	~0,023%
d SD	0,301%	0,406%	0,358%	~0,047%
d NC	0,516%	0,814%	0,696%	~0,104%
μ	2,50	3,46	3,13	~0,26

SYNTHESIS AND PROPOSED GUIDELINES FOR DS-4 URM BUILDINGS

Synthesis of Seismic Performance Before and after Retrofit

The comparative evaluation of the pushover results obtained for the existing and retrofitted configurations allows a clear synthesis of the seismic behaviour of unreinforced masonry (URM) buildings classified as DS-4. Despite differences in geometry, construction details, and diaphragm characteristics, the analysed buildings exhibit consistent performance trends that can be interpreted at a typological level.

In the existing condition, all buildings are characterized by limited lateral strength, reduced deformation capacity, and low global ductility. Normalized base shear ratios remain well below values typically associated with acceptable seismic performance, while near-collapse drift capacities indicate a narrow margin between severe damage and potential structural instability. This behaviour confirms the first working hypothesis (H1), namely that DS-4 URM buildings exhibit a predominantly brittle seismic response governed by shear-dominated mechanisms and inadequate structural connectivity.

After retrofit, a clear shift in seismic behaviour is observed across the entire dataset. Lateral strength increases significantly, near-collapse drift capacities expand substantially, and global ductility values consistently exceed those of the existing condition. These results confirm the second working hypothesis (H2), demonstrating that retrofit interventions targeting global connectivity, diaphragm action, and confinement of masonry walls are effective in promoting a more stable and ductile seismic response.

The consistency of improvement observed across all eight case studies, despite inevitable variability in individual configurations, supports the robustness of the adopted retrofit framework and justifies the derivation of generalized performance ranges.

Expected Seismic Performance Ranges for DS-4 URM Buildings (Existing Condition)

Based on the statistical synthesis of the pushover results, characteristic seismic performance ranges for URM buildings in the DS-4 damage state are proposed. These ranges, summarized in Table 6, are derived exclusively from real post-earthquake case studies and reflect the actual structural condition of severely damaged buildings prior to retrofit. The proposed ranges indicate that DS-4 URM buildings typically exhibit:

- low normalized base shear capacity, reflecting limited shear resistance of masonry walls;
- small drift thresholds associated with damage limitation and significant damage states;
- near-collapse drift ratios generally below 0.30%;
- global ductility values typically below 2.0.

These performance levels confirm the limited seismic reliability of DS-4 buildings and underline the necessity of retrofit interventions prior to continued use. From a practical perspective, the proposed ranges may be used as reference benchmarks during post-earthquake assessments to support rapid screening, prioritization of interventions, and preliminary evaluation of expected seismic capacity.

Table 6. Expected seismic performance ranges for DS-4 URM buildings (existing condition).

Parameter	Typical range
V_b/W	9-17%
d DL	0,08-0,1%
d SD	0,14-0,21%
d NC	0,19-0,36%
μ	1,4 – 1,9

Retrofit Target Performance Values for DS-4 URM Buildings (Retrofitted Condition)

The analysis of the retrofitted configurations allows the definition of realistic target performance values achievable through commonly adopted retrofit strategies when applied to DS-4 URM buildings. These values, summarized in Table 7, represent performance levels verified through nonlinear static analysis of real retrofitted buildings.

The proposed retrofit targets indicate that, following intervention, DS-4 URM buildings can reasonably achieve:

- normalized base shear ratios in the range of 0.20–0.30;
- significantly increased drift capacities at all performance levels;
- near-collapse drift ratios typically exceeding 0.50%;
- global ductility values in the range of approximately 2.5–3.5.

These target values do not represent theoretical upper bounds but rather achievable performance levels based on practical retrofit solutions designed in accordance with Eurocode 8 – Part 3. As such, they provide engineers with realistic expectations regarding the effectiveness of retrofit interventions and help avoid both under- and over-conservative design assumptions.

Table 7. Target seismic performance values for retrofitted DS-4 URM buildings.

Parameter	Typical range
V_b/W	20-30%
d DL	0,11-0,16%
d SD	0,30-0,46%
d NC	0,52-0,85%
μ	2,5 – 3,5

Practical Use of the Proposed Guidelines

The performance ranges and target values proposed in this study are intended to support engineering practice in post-earthquake contexts. Their main applications include:

- rapid evaluation of the expected seismic performance of URM buildings classified as DS-4;
- preliminary benchmarking of numerical assessment results prior to detailed verification;
- definition of retrofit objectives and target performance levels compatible with code-based assessment;
- comparison of alternative retrofit strategies at an early design stage.

It should be emphasized that the proposed guidelines are not intended to replace detailed numerical analysis. Rather, they provide a performance-oriented reference framework grounded in real building behaviour, which can assist engineers and decision-makers during the early stages of assessment and retrofit planning.

Limitations and Scope of Applicability

The proposed guidelines are derived from a limited dataset of low-rise URM buildings and should therefore be applied with appropriate engineering judgment. Their applicability to taller buildings, highly irregular layouts, or masonry typologies significantly different from those considered in this study may require additional verification.

Furthermore, the analyses are based on nonlinear static procedures and do not explicitly account for record-to-record variability or higher-mode effects. Future studies may extend the proposed framework through the inclusion of additional case studies, alternative retrofit solutions, and nonlinear dynamic analyses.

DISCUSSION

Interpretation of Results in Relation to State of The Art

The seismic performance ranges identified in this study can be interpreted in the context of existing research on unreinforced masonry (URM) buildings subjected to strong earthquakes. Previous studies based on macro-element modelling and post-earthquake assessments consistently report a brittle seismic response for damaged masonry structures, characterized by limited deformation capacity and early shear failure of load-bearing walls. The low normalized base shear ratios and ductility values obtained for the DS-4 buildings analysed here are therefore consistent with established observations reported in the literature for heavily damaged URM structures.

However, many existing studies focus either on single-building case studies or on idealized typological analyses, often without explicitly isolating buildings classified in advanced damage states. In this respect, the performance ranges derived from eight real DS-4 buildings provide an aggregated reference that complements state-of-the-art research by offering dataset-based benchmarks rather than isolated results. The observed near-collapse drift capacities below approximately 0.30% in the existing condition are in line with values reported for severely damaged masonry buildings in post-earthquake assessments following events such as Kraljevo (2010), Zagreb (2020), and Petrinja (2020), although direct comparison is often hindered by differences in damage classification criteria and modelling assumptions.

Effectiveness of Retrofit Strategies

The retrofit interventions analysed in this study lead to systematic improvements in strength, deformation capacity, and global ductility across all case studies. The post-retrofit ductility values, typically ranging between 2.5 and 3.5, are comparable to or slightly higher than those reported in several retrofit-oriented studies based on macro-element or equivalent-frame models. These improvements are primarily associated with enhanced diaphragm action, improved connectivity between structural components, and confinement effects introduced through perimeter reinforced concrete elements.

While similar retrofit strategies have been applied in other studies, the present work differs in that performance gains are evaluated consistently across multiple real DS-4 buildings using the same assessment framework. This allows the derivation of realistic target ranges for retrofitted configurations, rather than isolated performance indicators. The results confirm that, even for severely damaged URM buildings, retrofit interventions designed in accordance with Eurocode 8 – Part 3 can shift the global response from a brittle, shear-dominated behaviour towards a more controlled and ductile seismic performance.

Variability and Influencing Factors

Despite the overall consistency of trends, variability in seismic response is observed among the analysed buildings. Differences in diaphragm stiffness, wall layout, and damage distribution influence both strength and deformation capacity. Buildings with more effective diaphragm action generally exhibit higher ductility and more uniform force redistribution among walls, while structures with flexible diaphragms tend to show reduced deformation capacity and a stronger dependence on individual wall performance. Material variability also plays a role, although its influence is secondary compared to global structural configuration and connectivity. These observations highlight the importance of considering system-level behaviour when assessing and retrofitting URM buildings, rather than focusing solely on local wall capacity.

Methodological Considerations and Limitations

The seismic assessment is based on nonlinear static (pushover) analysis, which remains a widely adopted and practical tool for the evaluation of existing masonry buildings. While pushover analysis provides valuable insight into global capacity and deformation trends, it does not capture record-to-record variability or higher-mode effects. As a result, the proposed performance ranges should be interpreted as indicative benchmarks rather than precise predictive limits.

Damage was incorporated implicitly through reduced stiffness and strength parameters, an approach commonly adopted in post-earthquake assessments where explicit crack modelling is impractical. Although this introduces modelling uncertainty, the consistent methodology applied across all case studies ensures that comparative trends between existing and retrofitted configurations remain meaningful.

Implications for Practice and Future Research

From an engineering practice perspective, the results support the use of performance-based benchmarks derived from real buildings to inform post-earthquake decision-making. The proposed ranges can assist engineers in evaluating whether numerical assessment results are realistic and in defining retrofit objectives compatible with observed building behaviour.

Future research may extend the present framework through the inclusion of additional DS-4 case studies from different seismic regions, sensitivity analyses on key modelling parameters, and nonlinear dynamic analyses for representative buildings. Such extensions would further refine the proposed performance ranges and improve their applicability across a wider range of masonry typologies.

CONCLUSION

This study investigated the seismic performance and retrofit effectiveness of eight real unreinforced masonry (URM) buildings classified as DS-4 after the 26 November 2019 Albania earthquake. The work was based on consistent documentation for all case studies, including post-earthquake field inspections, laboratory characterization of masonry materials, numerical modelling using a macro-element approach, and nonlinear static (pushover) analyses. For each building, performance was evaluated in the damaged (existing) state and then re-evaluated after retrofit interventions designed in accordance with Eurocode 8 – Part 3.

The results obtained for the existing DS-4 condition confirm the expected vulnerability of severely damaged URM buildings. The analysed structures show low normalized base shear capacity, limited drift capacity at the defined performance levels, and low global ductility (typically below 2.0). This behaviour is consistent with a response governed mainly by in-plane shear mechanisms, compounded by inadequate diaphragm action and weak wall-to-floor connectivity deficiencies that were also evident during the field inspections.

After retrofit, all buildings exhibit a clear and repeatable performance improvement. The retrofitted configurations show a substantial increase in lateral strength and a marked expansion of deformation capacity, with near-collapse drift capacities increasing by more than 100% compared to the existing condition. Ductility values also rise significantly, typically exceeding 3.0, indicating a transition from brittle behaviour towards a more stable and controlled global response. These gains are associated with integrated retrofit actions that improve structural continuity and "box-type" behaviour, particularly through perimeter confinement elements, diaphragm stiffening, and strengthened connections.

Beyond the individual building results, a key outcome of the work is the synthesis of dataset-based benchmarks. Using the complete set of pushover results, the paper proposes typical seismic performance ranges for DS-4 URM buildings and realistic target values after retrofit, expressed through normalized base shear, drift limits at DL/SD/NC, and global ductility. These ranges are not meant to replace detailed assessment; instead, they provide engineers with practical reference values grounded in real post-earthquake case histories, supporting early-stage screening, benchmarking of numerical models, and definition of retrofit objectives.

The proposed ranges are derived from a limited number of low-rise URM buildings and should be applied with engineering judgment when dealing with taller or highly irregular masonry structures, or with typologies that differ significantly from those examined here. In addition, the study relies on nonlinear static procedures; further research could extend the framework through additional case studies, explicit uncertainty/sensitivity evaluation, and nonlinear dynamic analyses for representative buildings and retrofit variants.

AUTHOR CONTRIBUTIONS

Conceptualization, M.H.; methodology, M.H., and A.B.; software, M.H. and E.D.; validation, H.B.; formal analysis, M.H.; investigation, M.H.; resources, A.B.; data curation, M.H., and E.D.; writing—original draft preparation, M.H.; writing—review and editing, M.H., and H.B.; visualization, M.H., and E.D.; supervision, H.B.; project administration, M.H. and A.B.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest associated with this publication, and that no external financial support influenced the research outcomes.

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