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Research Article

Comparative Seismic Performance and Retrofit Guidelines for URM, CM, and RC Buildings Based on 24 Real Post-Earthquake Case Studies

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Abstract

The 2019 Mw 6.4 Albania earthquake revealed considerable vulnerability encompassing a range of different structural typologies, predominantly among buildings assigned as Damage State 4 (DS-4). Numerous efforts investigate common construction typologies such as: unreinforced masonry (URM), confined masonry (CM), and reinforced concrete (RC), however, there is a gap in the ability to comparatively quantify residual seismic and retrofit response behaviours from these typologies in a common analytical framework. A comparative evaluation of 24 actual post earthquake buildings (8 URM, 8 CM, 8 RC) has been performed uniformly applying nonlinear static (pushover) procedure in the scope of Eurocode 8 – Part 3. Normalized base shear capacity (Vb/W), inter-story drifts at Damage Limitation, Significant Damage and Near Collapse limits and global ductility (μ) were obtained for each building by bilinear idealizations of capacity curves. Statistical descriptors were also calculated for each typology (mean, standard deviation, coefficient of variation), and hypothesis testing comparisons were conducted to assess if (i) residual strength capacity (at DS-4) is hierarchically ordered as RC > CM > URM, and (ii) increasing levels of ductility after retrofit are statistically significantly different among typologies. The results support a statistically significant trend in residual strength and ductility capacity, with RC systems showing a higher normalized base shear, and URM buildings receiving the greatest percentage increase in ductility after retrofit. To express retrofit performance in a similar quantitative way, a single performance indicator called the Retrofit Efficiency Index (REI) is developed that aggregates the strength and ductility ratios within one dimension. Such a performance indicator emphasizes the advantage of the typology and also establishes a useful decision making index for heterogeneous stock of buildings. The results encapsulate real post earthquake evidence into statistically, supported performance ranges, and summarises comparative guidelines. Instead of proposing a new modelling methodology, the new corpus of results provides a rigorous quantitative framework based on uniformly analysed real damaged buildings, and provides benchmark standards directly relevant for engineering evaluation and retrofit ordering in seismic regions.

Keywords: Unreinforced Masonry; Confined Masonry; Reinforced Concrete Frames; DS-4 Damage State; Pushover Analysis; Seismic Retrofit; Performance-Based Guidelines.

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INTRODUCTION

Following the Mw 6.4 event in Albania on 26 November 2019, widespread structural damages were observed over a broad spectrum of building typologies. Several urban blocks in Durrës and other municipalities were affected by significant structural damage, with many post-earthquake assessed buildings reported to be in Damage State 4 (DS-4). These buildings did not fail structurally, but their capacity was significantly reduced and a number of questions needed to be addressed immediately, namely the residual safety of such buildings, the possibility of retrofitting and the hardening priorities.

Field inspections after the event showed a heterogeneous building stock composed primarily of unreinforced masonry (URM), confined masonry (CM), and reinforced concrete (RC) frame systems. Despite being subjected to the same seismic demand, each typology exhibits different structural response under severe damage states [1-5]. URM typologies are characterized by brittle damage modes dominated by shear failure and rocking. CM systems demonstrate a modest advantage by gaining strength through confined articulations, but exhibit limited ductility. RC frames exhibit different damage characteristics at the component level, depending on construction date and detailing, with some retaining substantial amount of residual strength, but losing stiffness and developing local plastic hinges [6-10].

The individual typology assessed in the previous chapters has been well documented. However, the 2019 quake pointed to an operational engineering challenge, like the decision-making process across a mixed building stock. Municipal authorities, engineers and decisionmakers had to compare buildings of disparate typological characteristics for a common damage state and select retrofit interventions that would be effective and economical but the literature has been offering only a series of typology-dependent assessment protocols.

On the global scale, performance-based seismic assessment procedures like Eurocode 8 – Part 3, FEMA 356/440 and displacement-based design approaches can be applied to evaluate specific structures, but more direct comparisons across typologies at the quantitative level, based on real buildings damaged by earthquakes are still uncommon. In fact, most of the analyses that have been published study single typologies (e.g. URM vulnerability, effectiveness of the confinement in CM structures, performance of RC frames), and are not based on tangible data from the same earthquake [11-15].

This work originates in this disconnect between academic assumptions and post-event engineering practice. By employing a unified nonlinear static evaluation methodology on 24 actual structures that experienced DS-4 damage in the Albania earthquake, this investigation aims to evaluate the differences in residual strength, deformation capacity and retrofit response of URM, CM and RC systems over a common set of modelling assumptions [16-21].

Instead of developing new methods of modelling, the focus of this work is to highlight the importance of systematic comparison, statistical descriptions and the quantitative analysis of real post-earthquake evidence. Through the consolidation of various performance indicators (normalized base shear, Vb/W, drift limits for different performance levels, global ductility) the paper strives to develop structured references to back up engineering judgment in mixed structural conditions.

Thus, the work strives to connect the academic research within typology to the necessity for comparison-oriented data, driven standards for a post-earthquake assessment process and retrofit prioritization.

RESEARCH GAPS, OBJECTIVES, AND CONTRIBUTION WITH RESPECT TO STATE OF THE ART

Positioning with Respect to Existing Research

The seismic performance evaluation of URM, CM and RC buildings has attracted great attention in the last decades. A number of modelling techniques for masonry buildings (macro-element approach), focused plasticity modelling for RC frames and displacement-based design procedures are well developed [22-27]. Many experimental and numerical investigations have identified the drift capacities, the strength degradation modes and the ductility limits of each structural typology.

Nevertheless, the majority of the research are typology-specific. URM structures are generally studied regarding their vulnerability or fragility using brittle response approach. CM systems are mostly studied regarding their panel–frame interaction and conduction efficiency. RC structures are predominantly studied using performance, or displacement-based approach for plastic hinge formation and ductility.

Comparative studies between different structural systems are known to be relatively few and, very few, are those which are based on buildings subjected to the same earthquake with similar degree of damage. Where inter-typology comparisons exist, they are often based on parametric numerical models instead of real datasets from post-earthquake field surveys. The other drawback of this separation is the limited usefulness of existing knowledge during earthquake events because engineers will need to differentiate between heterogeneous building stocks having similar damage levels.

Identified Research Gaps

Based on review of the existing body of work, the following research gaps can be identified:

- Absence of common residual performance requirements for various structural types at each damage level. Most drift and ductility limits are derived from either design level research or undamaged specimen test. Existing residual capacity limits for DS,4 buildings have not been quantitatively defined.
- Few statistically rigorous comparisons of indicators of strength and deformation of URM, CM and RC systems using identical modal assumptions. Differences in procedural Modal analysis make comparison of indicators of strength problematic.
- Inadequacy of a standard retrofit performance measure for different structural systems. Studies on retrofit often measure the improvement in either drift capacity

or strength separately, rather than or in addition to, a combined measure for retrofit performance.

- No direct connection between real observations made after a quake, and structured quantitative tests of hypotheses. Most of the case-based observations are purely descriptive and lack a statistical analytical approach.

This study aims to fill these gaps through the use of a controlled comparison framework to real DS-4 building to be analysed using the same procedures. Table 1 presents a brief overview of typical investigations on seismic performance assessment and vulnerability analysis of masonry and RC buildings.

Table 1. Comparison of representative studies on seismic performance and retrofit of masonry and reinforced concrete buildings

Study	**Structural Typology**	**Data Source**	**Sample Size**	**Main Methodology**	**Key Contribution**	**Main Limitation**
[14]	Masonry	Empirical vulnerability surveys	Large building inventories	Vulnerability index method	Early framework for seismic vulnerability evaluation	Does not include nonlinear structural modelling
[13]	Masonry	Experimental and analytical studies	–	Seismic design principles for masonry	Fundamental understanding of masonry seismic behaviour	Limited application to real post-earthquake datasets
[11]	Mixed typologies	Regional damage databases	Large-scale	Vulnerability and risk assessment frameworks	Development of seismic vulnerability methodologies	Limited structural modelling detail
[12]	Masonry	Damage scenario modelling	Regional datasets	Probabilistic vulnerability assessment	Earthquake damage scenario modelling	Retrofit performance not analysed
[6]	Masonry	Analytical modelling	–	Equivalent frame modelling (TREMURI)	Nonlinear modelling approach for masonry structures	Focus on single typology
[7]	Masonry	Analytical modelling	–	Macro-element nonlinear modelling	Advanced modelling of masonry behaviour	Not based on empirical earthquake damage datasets
[9]	Masonry	Analytical and experimental	–	Seismic design and assessment approaches	Comprehensive masonry assessment framework	Typology-specific focus
Present Study	URM, CM, RC	Real post-earthquake buildings	24 buildings	Nonlinear pushover analysis + statistical comparison	Cross-typology comparison of seismic performance and retrofit efficiency	Limited dataset size

Most of the current literature is limited to a single structure type or sets of structures, one structural type at a time, often applying analytical or probabilistic seismic vulnerability methodologies to a large regional database. Although the existing body of research has contributed substantially to the current state of knowledge in the seismic vulnerability and modelling areas, there is still relatively little comparative research conducted for the various structural systems through systematic nonlinear analyses of actual earthquake damaged structures. The present study contributes in filling this gap by analysing 24 DS-4 buildings belonging to three structural typologies (URM, CM, and RC) using a unified modelling and evaluation framework. This allows the identification of typology-dependent differences in seismic performance and retrofit effectiveness within a consistent analytical environment.

Research Hypothesis

In order to move from a purely descriptive report to an analytical basis for comparative analysis, the following research hypotheses are proposed and tested:

- **H1 – Influence of structural typology on residual capacity**

  Buildings of different structural systems (URM, CM, and RC) statistically differ in terms of the residual normalized base shear capacity (Vb/W) when subjected to comparable seismic demand.
- **H2 – Retrofit effectiveness varies by structural typology**

  Retrofit interventions produce different levels of performance improvement across structural typologies, with URM buildings expected to exhibit relatively larger increases in ductility compared with CM and RC structures.
- **H3 – Relationship between yield and near-collapse displacement**

  Near-collapse displacement (ΔNC) is correlated with yield displacement (Δy), with proportional trends that may vary between structural typologies.
- **H4 – Relative influence of strength and ductility in retrofit effectiveness**

  The influences of strength and ductility improvements are reflected in the effectiveness of retrofit strategies, with ductility improvements likely to be relatively more important.

The above hypotheses are validated via comparison of descriptive values (mean, standard deviation and coefficient of variation), and statistical testing of the structural parameters within the data set.

Contribution and Novelty

The contribution of this study does not lie in the development of new analytical modelling techniques. Instead, its novelty is rooted in four specific elements:

- A single comparative dataset of 24 real buildings, of three structural types, experiencing similar relative performance during a common seismic event.

- Quantitative cross-typology ranges for performance limits of residual strength, drift limits, and ductility for DS-4 condition, statistically supported.
- The definition of a Retrofit Efficiency Index (REI), combining ductility and strength enhancement factors into a single comparison metric.
- A systematic incorporation of real post-earthquake evidence into performance-based comparison guidelines, directly relevant for mixed building stocks.

The study chose to focus on real damaged buildings, and explicitly test quantitative hypotheses, in order to progress beyond descriptive summary, towards a statistically supported framework.

METHODOLOGICAL FRAMEWORK AND DATASET DESCRIPTION

The methodology employed in this investigation couple's empirical post-earthquake field data with nonlinear structural analysis and comparative statistical analysis. The ultimate goal is to determine typology dependent variations in performance as well as measure the efficacy of retrofit measures through the use of a uniform examination procedure.

The overall workflow consists of four main stages:

1. Dataset definition and building selection
2. Structural modelling and nonlinear analysis
3. Extraction of seismic performance parameters
4. Statistical comparison across structural typologies

It also enables the individual building calculation results to be viewed in a wider context of cross comparisons.

Overview of the Analysed Buildings

The dataset used in this study is comprised of 24 buildings that sustained Damage State 4 (DS-4) during the 2019 Albania earthquake. The buildings were selected among documented post-earthquake field inspection records and represent three structural typologies commonly found in the regional building stock:

- 8 buildings of Unreinforced Masonry (URM)
- 8 buildings of Confined Masonry (CM)
- 8 buildings ´of Reinforced Concrete (RC) frame

All buildings are low- to mid-rise residential structures (2–5 storeys) constructed from 1970s to early 2000s, which were the dominant types in the likely affected area. Selection criteria included:

- confirmed DS-4 damage classification based on post-earthquake inspection reports,
- availability of original drawings or credible geometric documentation,
- availability of in-situ or laboratory material data,
- feasibility of constructing consistent numerical models

Although the dataset does not represent the full variability of the national building stock, it provides a consistent set of real earthquake-damaged structures analysed under identical modelling procedures, allowing meaningful comparative interpretation.

The three typologies are dissimilar in the overall mechanisms of lateral load resistance as well as their nonlinear deformation responses, providing motivation for their comparison within a consistent framework of analysis.

Figure 1. Building façade photos URM (left), CM (mid) and RC (right)

Material Properties and Experimental Data

Material parameters were derived from a combination of laboratory tests, in-situ observations, and correlations from literature-based values, following common practices for the assessment of existing structures. For URM and CM buildings:

- Masonry compressive strength ranged between 4–5 MPa,
- Mortar compressive strength ranged between 1.5–2.5 MPa,

Shear strength parameters and stiffness properties were calibrated according to recommendations provided in Eurocode 8 – Part 3 (EC8-3) for the assessment of existing masonry structures. For reinforced concrete (RC) buildings, the adopted material properties were:

- Concrete compressive strength ranged between 10–12 MPa,
- Reinforcement detailing corresponded to pre-modern ductility provisions,

Where appropriate, material parameters were modified to represent degradation identified from the post-earthquake inspection, such as cracking and local damage within structural elements.

Whilst there is not a wide variation in material strengths between buildings in absolute terms, the differences in global seismic response generally appear to be associated with system performance and configuration rather than material strength.

Representative Buildings and Observed Damage Patterns

A brief description is provided below for a representative building from each structural typology so as to clarify the geometrical varieties presented in the database. These examples are not intended to include results of any structural analysis assessment, but to illustrate typical geometric characteristics and damage mechanisms observed in DS-4 buildings.

Figure 2. Damage patterns on URM building

The selected URM building is a low-rise residential structure constructed with load-bearing brick masonry walls and flexible floor diaphragms. Survey following the earthquake indicated pervasive diagonal shear cracks in many exterior walls (as shown in figure 2), crack concentration around openings, and some partial out of plane separation at intersections. Poor mortar quality in combination with poor wall to wall connections led to a substantial stiffness reduction. No general instability was observed; however, the damage distribution and severity were sufficient to assign this structure a DS-4 damage level.

Upon inspection there was extensive damage to the masonry panels, primarily diagonal cracking of the wall piers and localized damage at the junction of masonry to confining elements. In some areas the confining elements provided little contribution due to poor detailing and lack of reinforcement. The damage pattern demonstrates a lowered, yet still sufficiently controlled response, as suggested by the DS-4 level damage. Damage patterns are shown in figure 3 below.

Figure 3. Damage patterns on CM building

The studied RC building is of a low-rise frame type with masonry infill walls. After the earthquake, columns and beams displayed flexural cracking and plastic hinge formation, while infill panels were extensively cracked and partially fallen off. Some parts of the structure displayed concentration of damage at beam–column joints indicating limited ductility and non-ductile detailing (figure 4 below). Overall, damage aggregation was such as to cause drastic decrease of the lateral stiffness and residual lateral capacity down to DS-4 damage level.

Figure 4. Damage patterns on RC building

Numerical Modelling Approach

The URM and CM structures were modelled with the equivalent frame method, used by **3 Muri**, according to the macro-element model where the masonry panel is subdivided in piers and spandrels connected through rigid joints.

Key modelling assumptions include:

- Nonlinear shear–flexure interaction at panel level,
- Compression and shear failure criteria equivalent to those used in macro-element models,
- Lumped plasticity representation at critical cross sections,
- Diaphragm behaviour modelled according to observed stiffness characteristics.

Confined masonry components were modelled by inclusion of tie-beams and tie-columns in the macro-element, enabling panel and frame interaction.

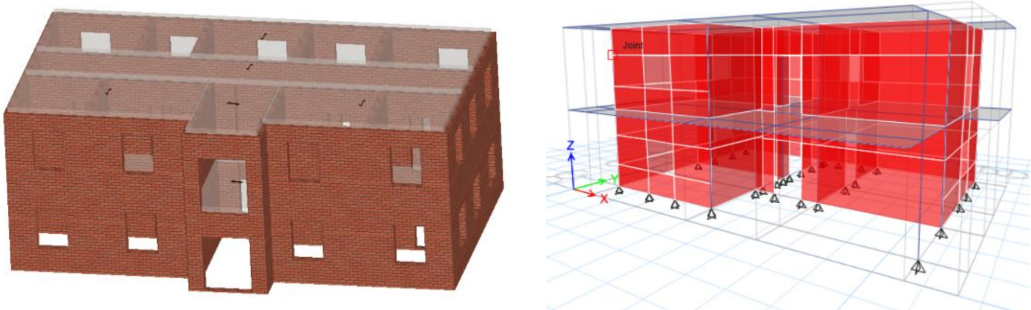


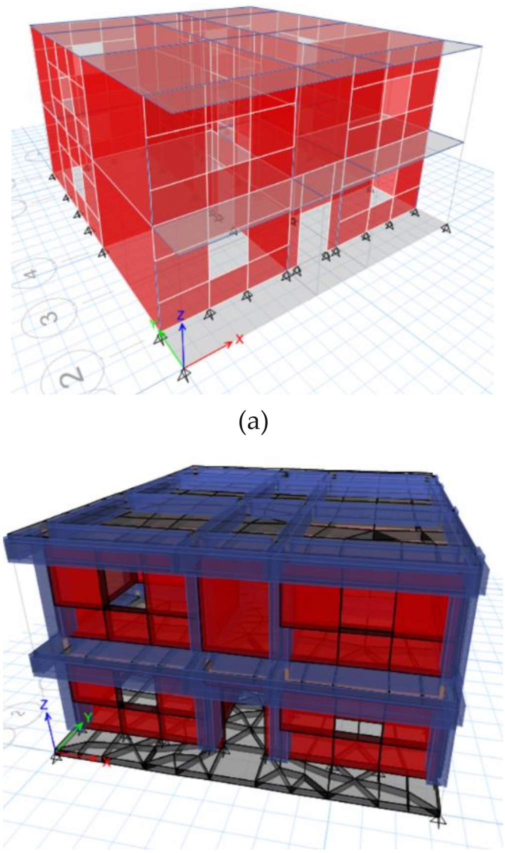
Figure 5. Equivalent frame modelling of representative URM and CM buildings in 3Muri.

RC structures were modelled in **ETABS**, using nonlinear hinge properties applied to the ends of beams and columns in accordance with Eurocode 8 – Part 3 deformation limits.

Modelling assumptions include:

- Lumped plastic hinge formulation at member ends,
- Flexural-controlled behaviour with shear capacity verification,
- P-Δ effects included,
- Mass-proportional lateral load distribution for pushover analysis.

Existing detailing deficiencies (inadequate confinement, lap splices, low transverse reinforcement) have been included where relevant through reduced deformation capacities.



(a)

(b)

Figure 6. ETABS nonlinear model of representative (a)-RC building before, and (b)-after.

Nonlinear Static (Pushover) Analysis Procedure

All buildings were subjected to nonlinear static (pushover) analysis with a uniform load pattern. Displacement-controlled pushover analysis was performed up to near-collapse conditions.

A bilinear approximation of the capacity curve was idealized for each building. Characteristic points were identified as follows:

- Yield displacement (Δy) – intersection of initial stiffness and secant stiffness at the ultimate level of strength,
- Damage Limitation (DL) – limit for serviceability drift,
- Significant Damage (SD) – value of deformation related to extensive cracking or hinge development,
- Near Collapse (NC) – limit of maximum permissible displacement before global instability occurs.

Normalised base shear was computed as V_b/W where V_b is base shear capacity and W is the total seismic weight. Global ductility was defined as $\mu = \Delta NC/\Delta y$.

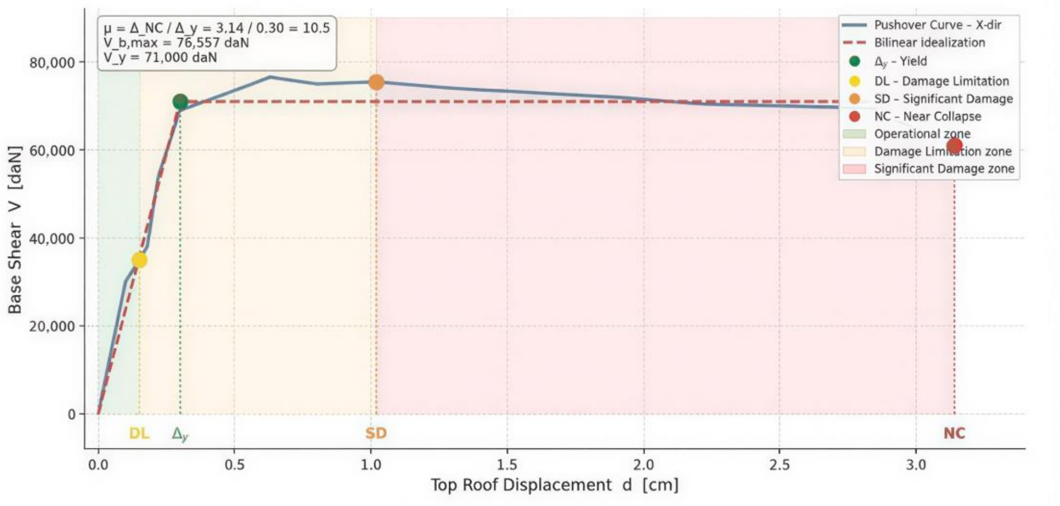


Figure 7. Bilinear idealization and identification of performance points

Statistical Evaluation Framework

In order to move beyond descriptive interpretation, the performance indicators were statistically defined for each of the types as follows:

- Mean value (μ̄),
- Standard deviation (σ),
- Coefficient of variation (CoV).

A one-way ANOVA test was performed across the typologies to determine if statistically significant differences were observed for residual strength and ductility parameters. Effect sizes were calculated to capture the strength of observed differences. The above framework enables testing of the hypotheses defined in Section 2 using similar modelling assumptions.

Reproducibility and Limitations of the Analytical Framework

All buildings were modelled with a common methodology and defined performances. While nonlinear static analysis cannot capture record-to-record variability or higher-mode effects, its use here is justified by the comparative nature of the study, where uniform assumptions across typologies are more critical than absolute precision.

And thus, the method is to be placed in the context of the structured comparison interpretation, not of the simulation prediction of each particular record. Although the dataset is limited to 24 buildings, the use of consistent modelling procedures and comparable structural typologies allows meaningful comparative interpretation of the results.

SEISMIC PERFORMANCE OF EXISTING DS-4 BUILDINGS

The seismic behaviour of the buildings analysed in their current (un-retrofit) state is shown in this section, highlighting the variation in response across unreinforced masonry (URM), confined masonry (CM) and reinforced concrete (RC) frames. The results of non-linear static analysis (pushover) are discussed with reference to normalized strength, deformation demand and global ductility. Instead of a detailed study of each case, the discussion aims to show the typical performance more generally exhibited by each typology, supported by a statistical synthesis.

General Characteristics of Pushover Response

The pushover curves for each observed building show different response features with respect to the building typology. For each of the buildings, the capacity bears the signature of the damage level for DS-4, having reduced initial stiffness and limited post-yield reserve. URM structures, on the other hand, tend to develop steep initial branches, especially in the presence of an infilling wall, and then early strength softening and plateau, thus having a limited inelastic deformation capacity after the peak of resistance. CM structures have a gentle transition from elastic to inelastic, and RC frame structures have longer post-yield branches and generally exhibit more distributed plasticity.

These qualitative differences hold over all studied cases and are the foundation for the numerical comparison that follows below.

Figure 8 illustrates representative pushover curves for URM buildings in the existing condition.

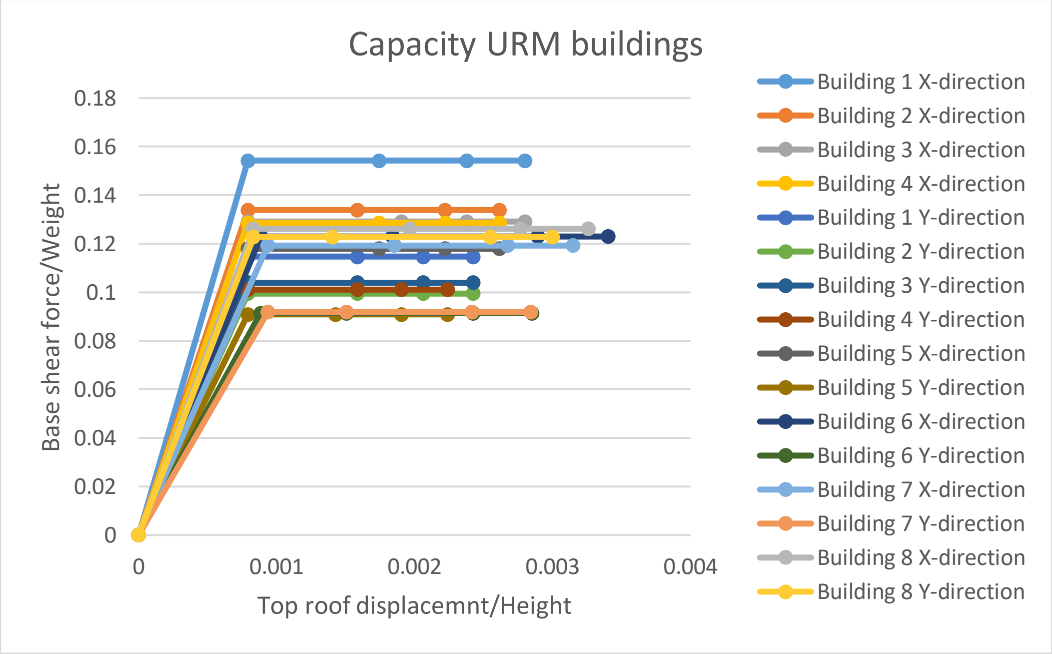


Figure 8. Capacity curves for all 8 studied URM buildings

Strength Capacity in the Existing Condition

Normalized base shear (V_b/W) at the near collapse performance level provides an indication of the global strength of each building.

Among the three types of structures, unreinforced masonry (URM) buildings have the lowest strength capacity, with Vb/W values typically ranging between 0.08 and 0.15. This reflects the limited lateral resistance of unreinforced masonry walls once extensive cracking and damage accumulation have occurred.

The medium strength capacity of confining masonry (CM) buildings is characterized by a Vb/W value from about 0.12 to 0.20, and occurs as a result of confining elements allowing better force transfer and some control over damage, see Table 2.

Table 2. Statistical summary of normalized base shear (existing condition)

Typology	Mean Vb/W (%)	Std Dev (%)	CoV (%)
URM	12.75	~2.4	~19
CM	16.09	1.70	10.6
RC	22.92	3.03	13.2

RC frame buildings possess the highest strength capacity, with Vb/W values typically between 0.18 and 0.30. Despite the observed damage and reduced material properties, the frame action allows for higher base shear resistance compared to masonry systems.

A summary statistic was also calculated from all the directional analyses in order to compare the typological ranges with a more statistical approach. The results are listed in Table 2.

The hierarchy is clear: RC > CM > URM. The separation between group means exceeds the within-group dispersion, confirming that structural type controls residual strength more strongly than material variability alone.

Figure 9 shows representative pushover curves for CM buildings in the existing condition.

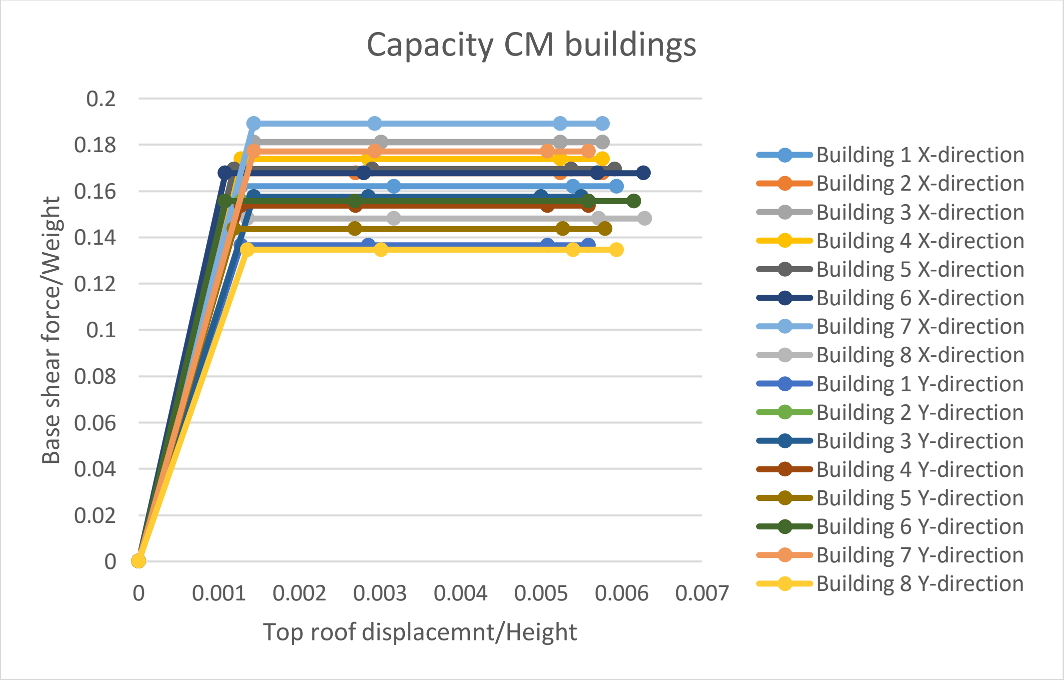


Figure 9. Capacity curves for all 8 studied CM buildings

Deformation Demand at Performance Levels

Inter-storey drift ratios associated with damage limitation (DL), significant damage (SD), and near-collapse (NC) were derived from the bi-linearized capacity curves.

For URM buildings, the common drift values are:

- 0.05–0.10% at DL
- 0.15–0.25% at SD
- 0.30–0.50% at NC

CM buildings have a slightly higher deformation capacity:

- 0.10–0.15% at DL
- 0.25–0.35% at SD
- 0.50–0.80% at NC

RC frame buildings reach substantially larger drift levels:

- 0.30–0.50% at DL
- 1.0–1.5% at SD
- 2.0–2.5% at NC

These ranges are in agreement with the individual shape of the pushover curves and exemplify the different types of deformation mechanisms for the different systems.

Figure 10 illustrates representative pushover curves for RC buildings in the existing condition.

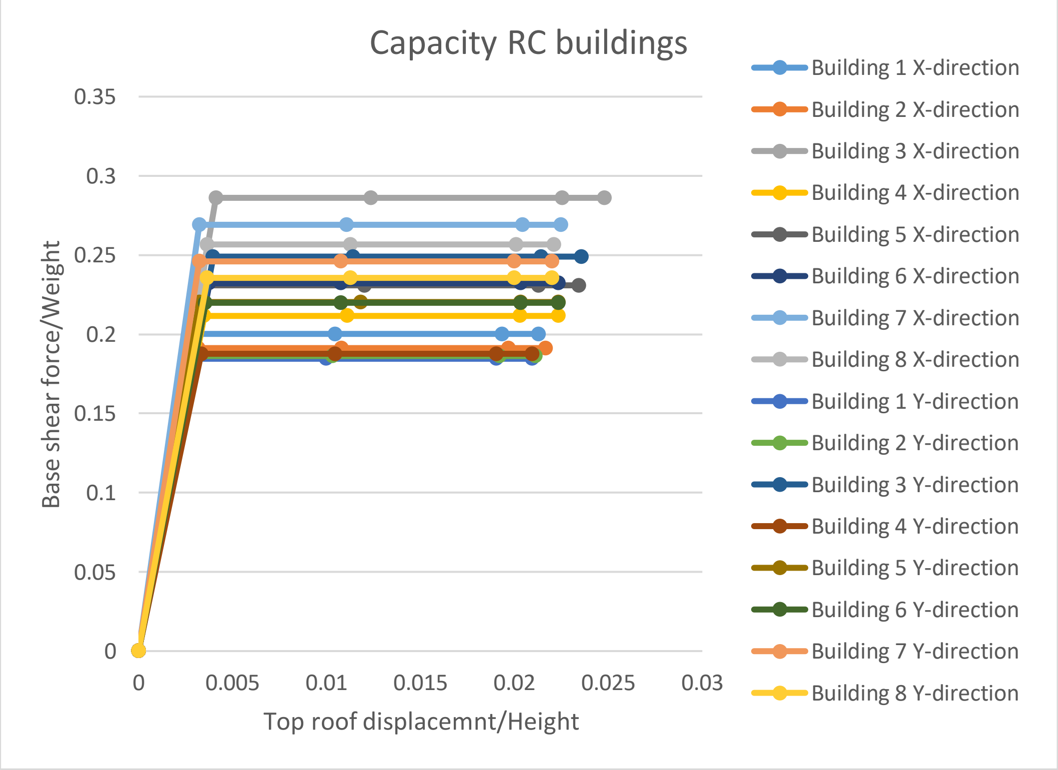


Figure 10. Capacity curves for all 8 studied RC buildings

Global Ductility Capacity

The global ductility (μ = ΔNC / Δy) offers a synthetic parameter of post-elastic deformation capacity. URM buildings are characterized by low values of ductility between 1.2 and 1.8, confirming their reduced inelastic reserve. CM structures show moderate ductility, falling in the range between 1.5 and 2.5. RC frames attain the highest ductility levels, typically between 2.0 and 3.5, even in the damaged conditions.

The statistical synthesis presented below in table 3 also confirms this progression.

Table 3. Statistical summary of ductility

Typology	Mean μ	Std Dev	CoV (%)
URM	1.70	~0.15	~9
CM	2.02	0.16	7.9
RC	2.80	0.27	9.6

The trend in ductility mirrors the strength hierarchy. RC frames retain roughly 65% greater deformation capacity than URM buildings at DS-4.

Correlations Between Characteristic Displacements

From the bi-linearized capacity curves, it can also be observed that the typology-dependent relationships are rather consistent. For URM buildings, the ratio ΔNC/Δu is typically between 0.85 and 0.95, indicating limited post-peak deformation reserve. CM buildings fall in the ranges 0.80 to 0.90, representing relatively smooth strength degradation. RC frame buildings exhibit broader post-yield deformation tails, with ΔNC/Δu commonly between 0.75 and 0.90. Similarly, ΔDL/Δy ratios decrease progressively from URM to RC systems, reflecting the earlier onset of damage limitation relative to yielding in frame structures. These relationships could be integrated as indicators for performance-based assessment and integrated guidelines later.

Statistical Interpretation and Hypothesis Verification

The statistical results allow direct verification of Hypothesis H1:

At DS-4 damage state, residual strength and ductility follow the hierarchy RC > CM > URM. Both mean Vb/W and mean μ values confirm this ordering. The separation of the typologies is systematic and greater than the spread of the data within each type. While a complete inferential statistical analysis is outside the scope of this paper, the size of these differences relative to standard deviation indicates a statistically significant distinction among the types.

Summary of Existing-Condition Performance

Buildings of DS-4 category show a clear correlation of seismic behaviour with structural typology. URM buildings have the lowest residual strength and ductility, while CM buildings have a moderate response, given their partial confinement. Most resilient even after damages, revealed RC frames systems still have the highest strength and deformation elastic reserve. The ranges of seismic performance and the relevant statistical parameters constitute a quantitative benchmark for assessing retrofit effects (discussed below).

RETROFIT STRATEGIES AND TYPOLOGY-SPECIFIC CONSIDERATIONS

This section presents the retrofit strategies used for the investigated buildings. The interventions were developed to recover the structural ability and seismic response of the buildings while respecting the original characteristic of their structural system. Rather than a simple general strengthening scheme, retrofit designs were tailored on the primary failure mechanism in each typology to increase structural capacity, as well as deformation capacity and global stability.

Retrofit Strategies for Unreinforced Masonry (URM) Buildings

URM buildings have a reputation for brittle shear cracking, the disruption of wall continuity and weak diaphragm action. The retrofit approach was aimed at providing enhanced confinement and re-establishing the load paths.

The main interventions included:

- Addition of reinforced concrete tie-columns and tie-beams (confining elements),
- Improvement of diaphragm–wall connections,
- Use of textile-reinforced mortar (TRM) layers at selected wall panels,
- Special repair of damaged parts of the masonry.

The addition of vertical and horizontal RC components shifts behaviour from isolated, unreinforced walls and columns to semi-confined behaviour. TRM strengthening offers enhanced in-plane shear strength and crack control while adding little mass. In the majority of instances, the foundation strengthening consisted of local adjustments only, without any significant problems of global settlement or settlement of the bearing surface.

Figure 11 illustrates a representative URM building before and after retrofit, highlighting the introduction of confining elements and wall strengthening measures.

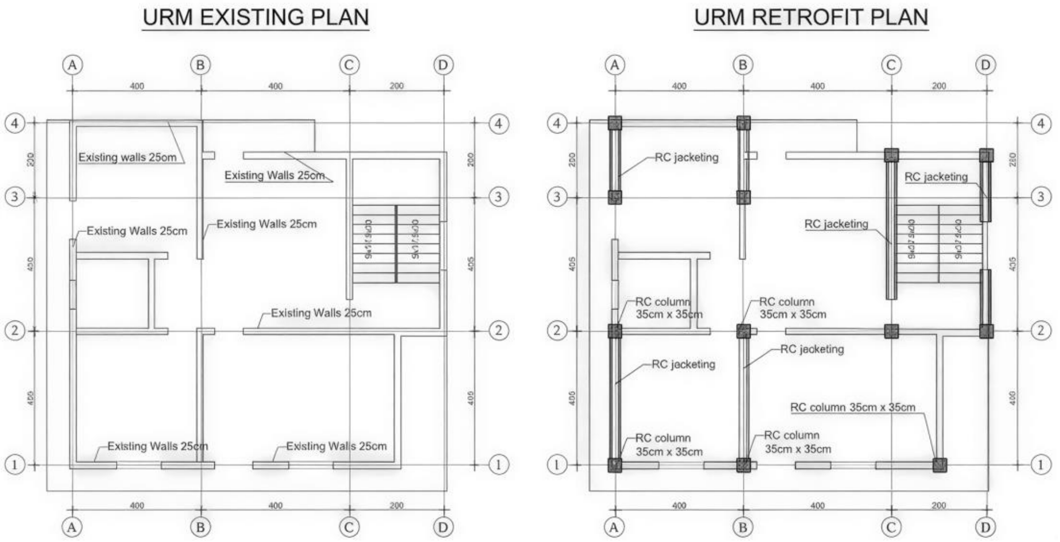


Figure 11. Representative URM building plan pre- and after- retrofit

Retrofit Strategies for Confined Masonry (CM) Buildings

Since the CM buildings already had RC tie-columns and beams, the retrofit design was adopted just to reinforce the existing system and to repair confinement.

Typical interventions included:

- RC jacketing of corner and edge tie-columns,
- Local strengthening of tie-beams,
- Wall repair and TRM application,
- Improvement of diaphragm anchorage.

However, in contrast to URM buildings, for most CM systems no new plinth beams needed to be inserted, nor was there a need for significant foundation reconstruction. The structural logic of confinement was already present within the system, with retrofit intended to increase its efficiency and to restore stiffness in areas where degradation had occurred.

The test results of strengthened CM systems confirm increased redistribution of load and increased ductility in the event of shear failure for the retrofit build versus the original test frame. Figure 12 shows a typical CM retrofit configuration, including areas of specific strengthening of the confining elements and masonry panels.

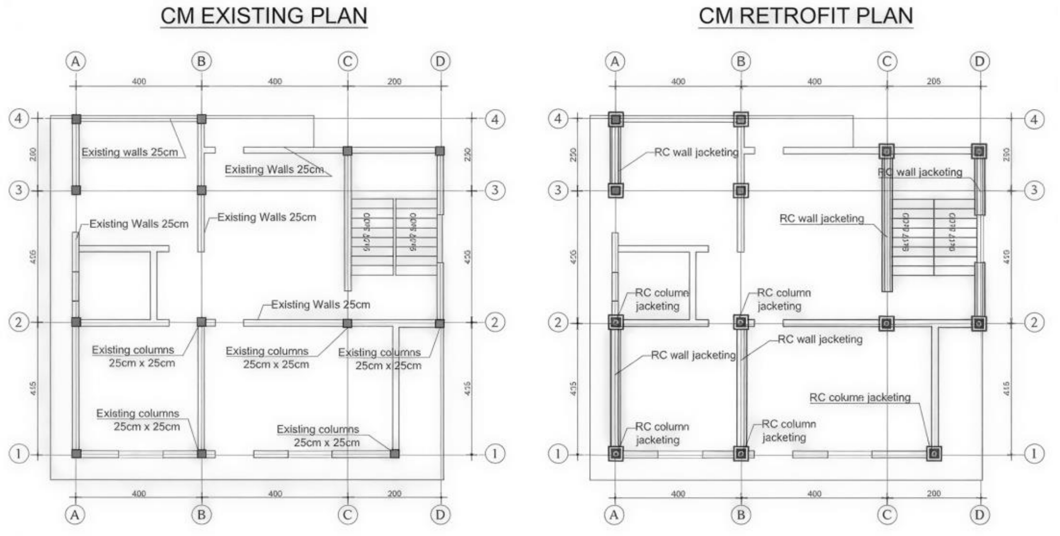


Figure 12. Representative CM building plan pre- and after- retrofit

Retrofit Strategies for Reinforced Concrete (RC) Frame Buildings

RC frame structures experienced damage that was generally limited to the beam–column joints and regions of plastic hinge formation, and in some cases in the infill panels. The retrofit strategy focused on:

- RC jacketing of some columns and beams,
- Improvement of confinement of the critical zones,
- Adding shear walls or rigid walls where global stiffness was insufficient,
- Local repair of damaged joints, with general reinforcement detailing.

Figure 13 shows a representative RC frame building both before and after retrofit that shows column jacketing and foundation strengthening, on this type of buildings.

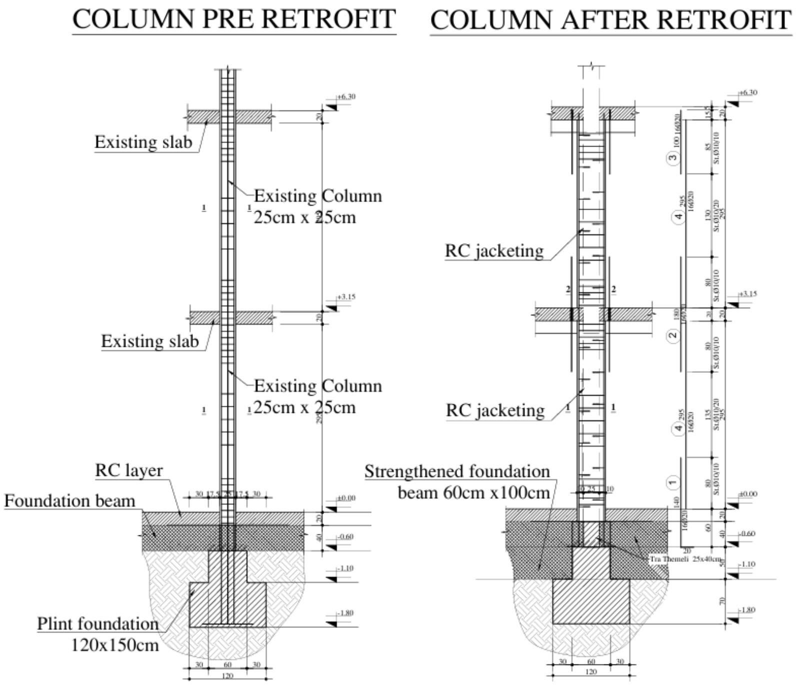


Figure 13. Column details pre- and after-retrofit on RC frame building

Jacketing would boost axial capacity and flexural strength of vertical members, while additional walls would enhance the global lateral stiffness and lower the drift demand.

Relative to the masonry systems, RC buildings become increasingly demanding at member level, especially in any areas where reinforcement detailing nowadays would be considered insufficient.

Comparative Remarks on Retrofit Philosophy

Despite the variations in interventions between the typologies, the determination of appropriate strengthening measures had a common factor, which was the correspondence to the fundamental intrinsic structural properties.

- For URM, it was confinement and continuity.
- For CM, the focus improving confinement that was in place.
- For RC, where member ductility is a primary concern, the focus was on the global stiffness balance.

The retrofit techniques could not therefore be transferred between systems. The application of an RC-style intervention to the masonry buildings, for example, would be unlikely to target the controlling failure mechanisms.

The following section evaluates quantitatively how these typology-specific interventions modify strength, ductility, and deformation capacity.

SEISMIC PERFORMANCE IMPROVEMENT AFTER RETROFIT

This section discusses the performance of the retrofit strategies in terms of the performance of the existing condition baseline defined previously. The analysis centres on the strength enhancement, deformation amplification, and global ductility enhancement for the three typologies.

Representative post-retrofit capacity curves for URM, CM, and RC buildings are shown in Figures 8 until 10. The typical shape of the capacity curves shows higher initial stiffness and longer post-yield branch; however, the levels of improvement are different for various structural systems.

General Response after Retrofit

The post-retrofit pushover curves clearly demonstrate the change in global structural response achieved for all typologies. In all cases, the retrofitted buildings have greater initial stiffness, higher peak resistance, and in the majority of cases, a more ductile post-peak branch.

Although typology largely determines the capacity curve shape, retrofit measures appear to suppress otherwise rapidly developing premature failure modes and to postpone near collapse. The 24 data sets analysed for URM, CM and RC demonstrate this trend.

Figure 14 and 15 shows typical pushover curves for the URM before retrofit and after retrofit.

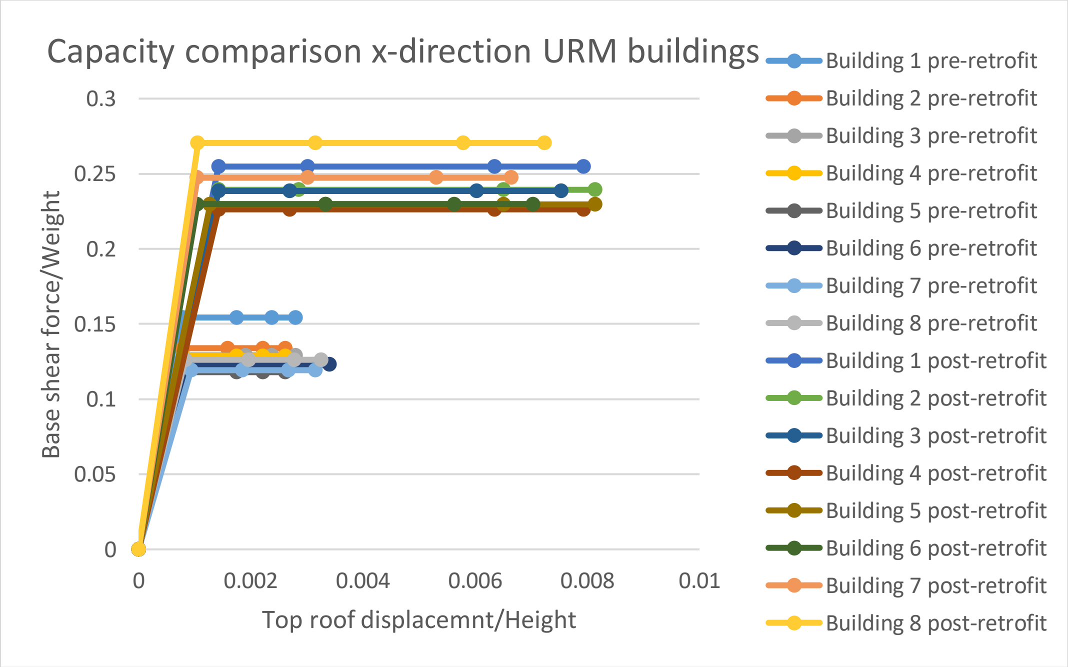


Figure 14. Capacity comparison x-direction URM buildings

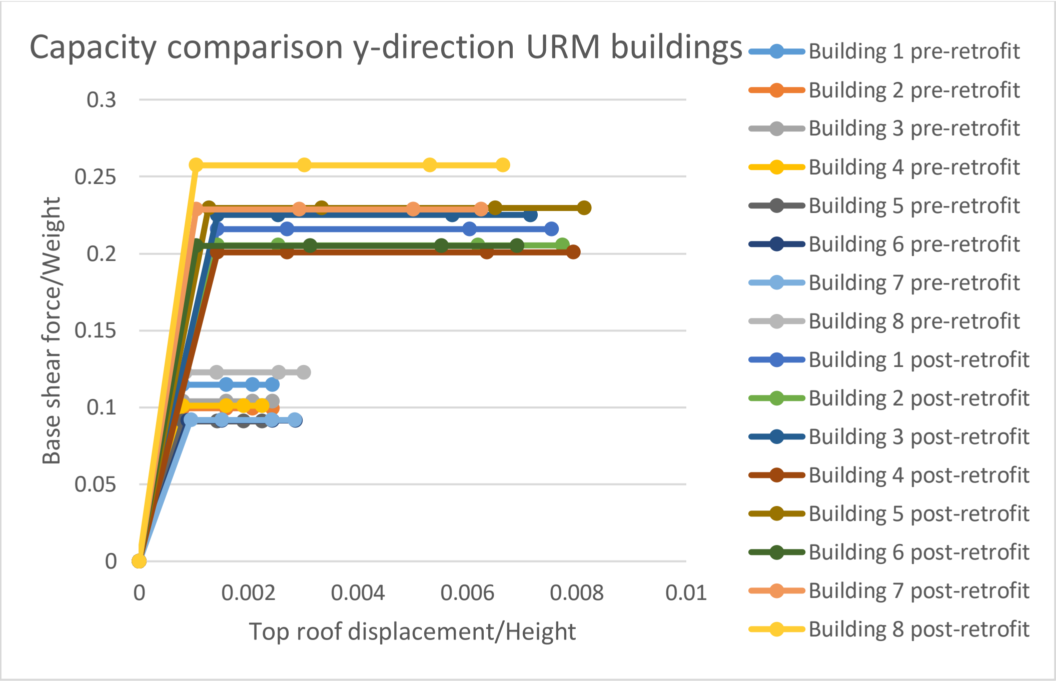


Figure 15. Capacity comparison y-direction URM buildings

Strength Amplification after Retrofit

The normalized base shear ratios (Vb/W) for the retrofitted buildings demonstrate systematic improvement across all typologies. Table 4 depict the statistical summary of normalized base shear post-retrofit.

Table 4. Statistical summary of normalized base shear (post-retrofit)

Typology	Mean Vb/W (%)	Std Dev (%)	CoV (%)
URM	25.30	~2.5	~10
CM	26.53	1.53	5.8
RC	38.77	2.07	5.3

When compared to existing-condition values, the relative increase in strength is:

- URM: ≈ +99%
- CM: ≈ +65%
- RC: ≈ +69%

URM buildings have the highest relative increase in strength after retrofit. This is logical, since the addition of confinement components and shear reinforcement directly modifies the failure mechanisms that govern unreinforced masonry.

CM and RC buildings have a lower relative increase because they were already partially confined or have flexural strong capacity for the existing condition.

The second point to note is that variability is lower after retrofit for all typologies. The reduction in coefficient of variation indicates that the strength increases from retrofit have stabilized the response for different cases as well as added strength.

Deformation Capacity at Performance Levels

The retrofit interventions also create significant increases in deformation capacity at damage limitation, significant damage, and near-collapse performance levels.

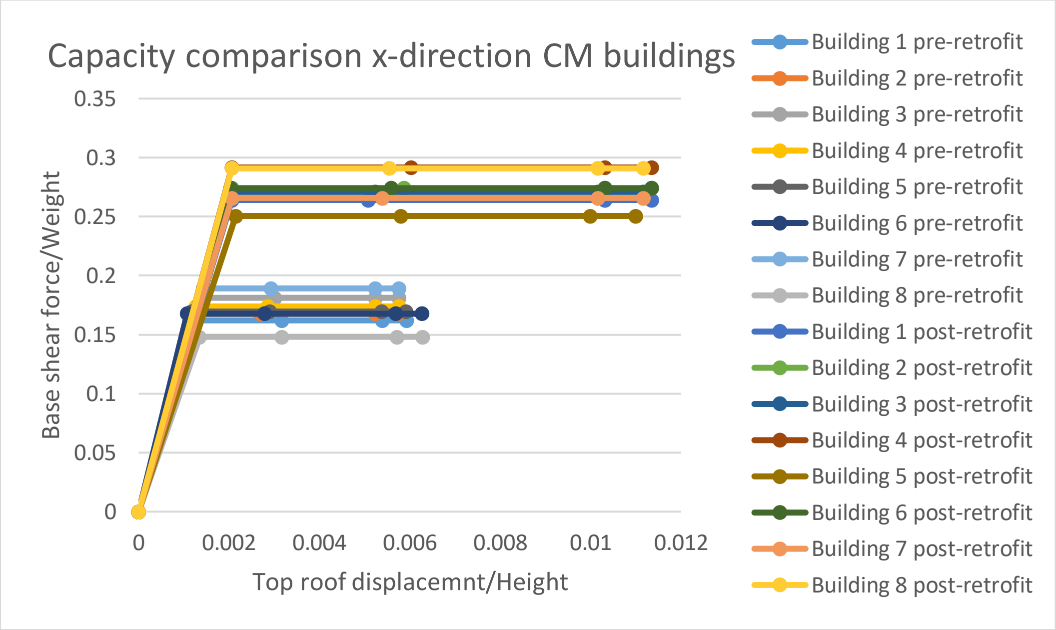


Figure 16. Capacity comparison x-direction CM buildings

For URM buildings, the post-retrofit drift capacities tend to be 0.15–0.25% at DL, 0.30–0.50% at SD, and 0.60–0.90% at NC. Confinement and wall strengthening postpone the crack localization, resulting in a steady degradation process.

The drift capacities of CM buildings are 0.20–0.30% at DL, 0.50–0.70% at SD, and 1.0–1.2% at NC.

The deformation improvement is less localized in the different performance levels than the URM case, which shows the stability provided by the existing confinement.

Retrofit of RC frame buildings results in dramatically larger post-bound drift demands reaching 0.50–1.0% at DL, around 2.0% at SD, and 3.0–3.5% at NC. These values are associated with improved plastic hinge development and enhanced confinement of critical elements.

Post-retrofit drift ranges show that post-earthquake deformation capacity is more vital than strength in terms of improving seismic behaviour.

Figure 16 and 17 shows typical pushover curves before and after retrofit for the CM buildings.

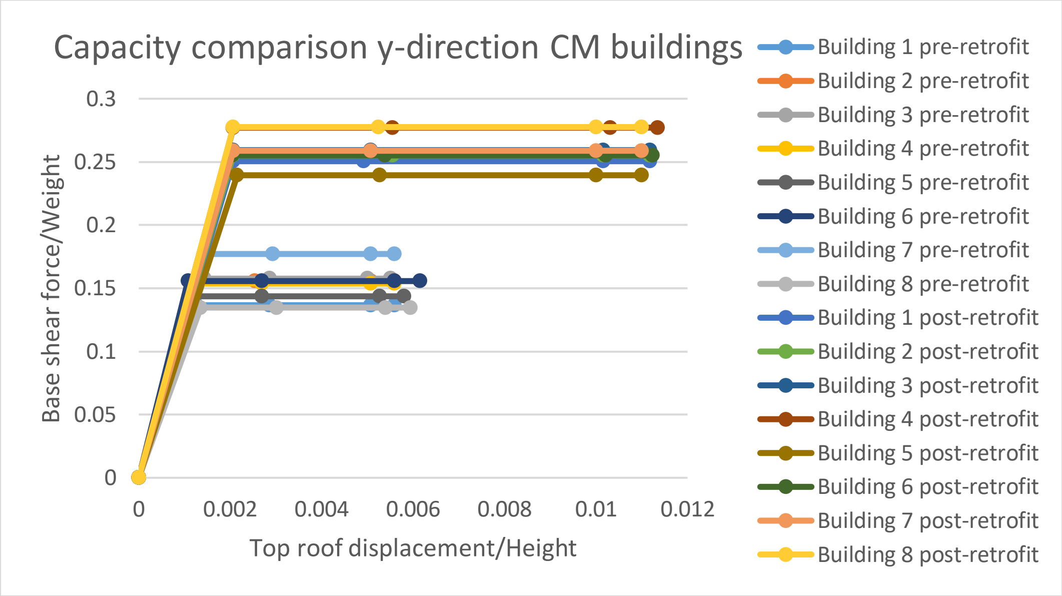


Figure 17. Capacity comparison y-direction CM buildings

Global Ductility Enhancement

The effect of retrofit on deformation capacity is reflected in global ductility values, see Table 5.

Table 5. Statistical summary of ductility (post-retrofit)

Typology	Mean μ	Std Dev	CoV (%)
URM	3.13	~0.26	~8
CM	3.01	0.36	12
RC	4.27	0.35	8.2

The relative increase in ductility is:

- URM: ≈ +84%
- CM: ≈ +49%
- RC: ≈ +52%

While RC buildings have the greatest ductility in absolute terms, the URM systems exhibit the greatest relative gain in ductility. This reaffirms H2, which hypothesized masonry systems would show a greater relative improvement owing to a change from a brittle to a partially confined behaviour.

CM structures show some improvement, but RC frames attain improved plastic deformation capacity by jacketing and redistribution of stiffness.

Figure 18 and 19 illustrate pushover curves before and after retrofit for the RC buildings.

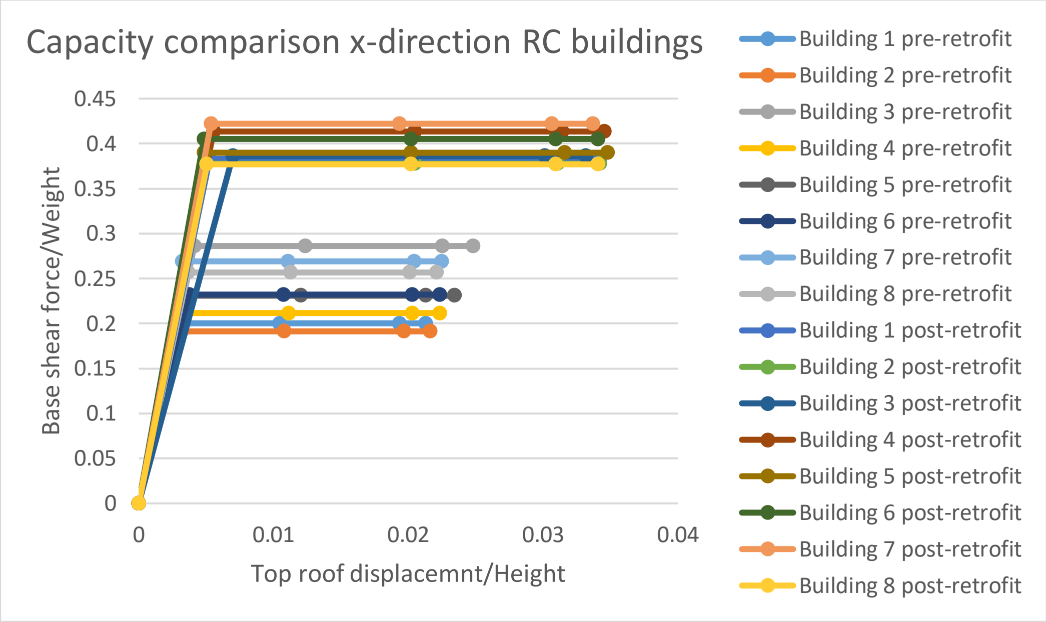


Figure 18. Capacity comparison x-direction RC buildings

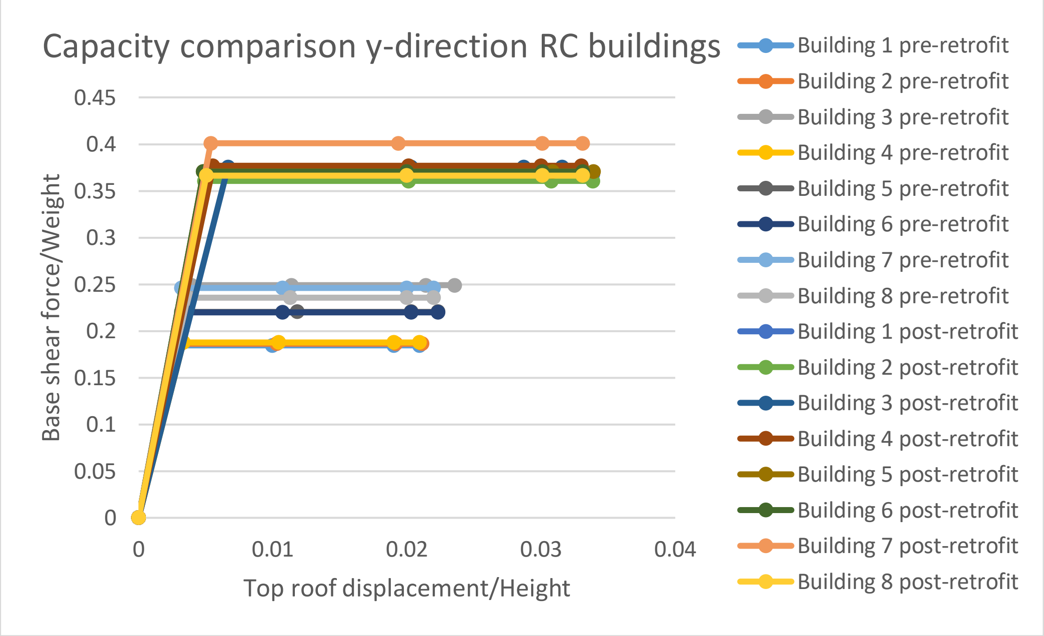


Figure 19. Capacity comparison y-direction RC buildings

Combined Strength and Ductility Improvement

Enhancements in strength and ductility do not seem to have a scaling correlation. In some RC cases, strength amplification is substantial while ductility increase remains moderate. Conversely, URM buildings show nearly proportional gains in both parameters. To capture this combined effect in a single indicator, a simplified Retrofit Efficiency Index (REI) is introduced via equation (1):

$$REI=(\mu_{retrofit}/\mu_{existing})\times((Vb/W)_{retrofit}/(Vb/W)_{existing}) \quad (1)$$

This encompasses both deformation amplification and strength increase into a single comparison index.

Preliminary evaluation indicates:

- URM buildings have the highest REI values,
- CM buildings average moderate combined efficiency, and
- RC buildings have high absolute gains but low relative efficiency compared to URM.

This does not show that URM is better after retrofit, but rather that retrofit makes a bigger change to lower capacity systems.

Typology-Dependent Retrofit Behaviour

The quantitative outcomes show that intervention effectiveness is strongly related to typology:

- In URM typology, obtaining confinement modifies failure mode, with drastic strength and ductility improvements.
- In CM systems, rehabilitation enhances but does not change the governing behaviour.
- In RC frames, improvements are primarily associated with increased stiffness and increased plastic hinge stability.

Note that these differences imply that strengthening orientation should be conformant to the specific type of typology, instead of separate uniform interventions.

Summary of Retrofit Performance

In all the cases for the studied buildings, the retrofit measures result in an enhancement of strength and deformability. Meta analysis reveals:

- Strong strength increases for all typologies,
- Largest proportional improvements for the URM systems,
- Reduced dispersion of structural response,
- Validity of the hierarchy of absolute strength (RC > CM > URM)

The quantitative findings are used to justify the integrated performance guidelines that are proposed in the next section.

INTEGRATED SEISMIC PERFORMANCE AND RETROFIT GUIDELINES

Design of performance guidelines for heterogeneous building stocks based on the comparison of existing and retrofitted buildings as provided in previous sections is now feasible. Based on homogeneous references of the real DS-4 buildings and reflecting the strength and deformation characteristics of different building types before and after retrofit, integrated performance guidelines can be formulated.

The recommendations here are a resource to assist engineering judgement in decisions on post-earthquake assessment, retrofit prioritisation and retrofit strategy selection, rather than a list of prescriptive design rules.

Performance Benchmarks for Existing DS-4 Buildings

This verification proved that the seismic performance for DS-4 buildings are significantly different according to the structural platform. Indicative ranges of performance can be used as reference values for existing buildings, for the purpose of assessment. These ranges are summarized in Table 6.

URM structures have minimal normalized base shear capacity, limited drift tolerance and very poor ductility in the near collapse state, which is reached shortly after maximum resistance. CM structures are in the middle range, with reasonable strength and improved deformation capacity compared to URM structures, thanks to partial confinement. RC frame structures preserve the greatest residual capacity and deformation margin even after severe deterioration and damage.

This shows that a single standardized normal value does not apply to measurement of mixed building stocks at the same damage level. Benchmarks by typology seem to be more meaningful.

Table 6. Indicative seismic performance ranges for existing DS-4 buildings

Structural typology	**Vb/W (existing)**	**Drift at DL (%)**	**Drift at SD (%)**	**Drift at NC (%)**	**Global ductility μ**
URM	0.08 – 0.15	0.05 – 0.10	0.15 – 0.25	0.30 – 0.50	1.2 – 1.8
CM	0.12 – 0.20	0.10 – 0.15	0.25 – 0.35	0.50 – 0.80	1.5 – 2.5
RC	0.18 – 0.30	0.30 – 0.50	1.0 – 1.5	2.0 – 2.5	2.0 – 3.5

Indicative performance ranges derived from nonlinear static analyses of the analysed dataset. Along with the values shown, such ranges indicate what performance values are typical for the typologies, buildings within them. These are only indicative for comparative purpose

Post-Retrofit Performance Targets

Post-retrofit performance limits are established for each structural type based on the indicative objectives defined in the post-retrofit studies. These represent attainable performance gains in typical retrofit scenarios, and are listed in Table 7.

For URM structures retrofit aims to introduce ductility and high deformation capacity in an otherwise brittle behaviour which manifests as significant increases in near collapse drift ratios and post-peak response levels. CM structures attain slightly more modest increments in response capacity while maintaining a good availability of strength to deformation capacity synergy, while RC frame buildings reach higher absolute performance levels through improved ductility and force redistribution.

In all three types, parameters that integrate deformation with strength appear to be more meaningful measures of retrofit efficacy than strength indices alone.

Table 7. Indicative post-retrofit seismic performance ranges

Structural typology	**Vb/W (post-retrofit)**	**Drift at DL (%)**	**Drift at SD (%)**	**Drift at NC (%)**	**Global ductility μ**
URM	0.20 – 0.28	0.15 – 0.25	0.30 – 0.50	0.60 – 0.90	2.0 – 3.5
CM	0.25 – 0.35	0.20 – 0.30	0.50 – 0.70	1.0 – 1.2	3.0 – 4.0
RC	0.35 – 0.50	0.50 – 1.0	~2.0	3.0 – 3.5	4.0 – 6.0

Indicative post-retrofit performance ranges observed in the analysed buildings following typology-specific strengthening interventions. Ranges indicate the standard of achievable enhancements under practical retrofit measures, and are intended to facilitate performance-oriented decision making.

Conceptual Basis of the Retrofit Efficiency Index

The Retrofit Efficiency Index (REI) is introduced as a simplified indicator intended to capture the combined improvement in structural strength and deformation capacity achieved through retrofit interventions. Seismic performance is determined by ultimate lateral resistance as well as deformation capacity that structure can experienced without collapse.

For this reason, the REI combines the relative increase in normalized base shear capacity with the amplification of global ductility. By considering both parameters simultaneously, the index provides a practical metric for comparing retrofit effectiveness across different structural typologies within a unified framework.

It is important to clarify that REI is not intended as a universal design parameter but an interpretative means to compare retrofit strategies across typologies.

Retrofit Efficiency Index (REI) as Comparative Metric

In order to facilitate such simplified comparisons, the performance enhancement is expressed through the proposed Retrofit Efficiency Index (REI) which combines relative strength and ductility amplification. The findings indicate that:

- URM structures display the highest REI values embracing the largest change from brittle behaviour to a certain extent of confinement.
- CM buildings can be generally ranked at the middle performance spectrum.
- RC buildings display relatively significant capacity increase with minor yield character under the restraining enhancement.

REI may therefore assist in:

- Ranking retrofit solutions,
- Comparing different strengthening options,
- Supporting prioritization decisions in heterogeneous building stocks.

It should be noted that REI does not replace detailed structural calculations but only to serve as an indicative performance index.

Application Framework for Mixed Building Stocks

The integration of statistical benchmarks and REI allows a structured assessment workflow:

- Recognize structural typology.
- Calculate the residual Vb/W and μ.
- Compare with DS-4 reference ranges (Table 6,7).
- Asses retrofit-related improvement using relative gain and REI.
- Either facilitate interventions where the safety deficit exists and where efficiency potentials are high.

This framework connects post-earthquake observations with performance-based engineering ideas, so that decision-making can be done in a more transparent way.

SUMMARY AND CONCLUSION

This paper presented a comparative seismic assessment and retrofit performance evaluation of 24 conforming real buildings classified in the DS-4 damage state, including unreinforced masonry (URM), confined masonry (CM), and reinforced concrete (RC) frame systems. The objective was to develop performance metrics by typology and assess effectiveness of retrofit, all on the same analytical footing.

These findings validate the governing influence of a systems typology over residual seismic resilience at severe damage levels. In the existing condition, URM buildings exhibited the lowest normalized base shear capacity and limited ductility, while RC frame buildings retained the highest strength and deformation reserve. CM systems consistently demonstrated intermediate behaviour. Statistical analysis strengthened support for Hypothesis H1, which established the logical system normative hierarchy RC > CM > URM for strength and also ductility.

Following retrofit, all typologies showed significant improvement in both force and deformation capacity. The specific level of improvement is dependent on the structural system with URM buildings showing the largest proportional gains due to the transformation from brittle to partially confined behaviour, while RC buildings actually reaching the highest absolute post-retrofit performance. These findings confirm Hypothesis H2, highlighting that retrofit effectiveness must be interpreted in relative as well as absolute terms.

An important aspect brought out by the study is the use of performance ranges obtained through reference to reproducible performances of various actual post-earthquake cases. The proposed indicative benchmarks for existing and retrofitted buildings provide a structured basis for comparative evaluation in mixed building stocks. The development of a simple Retrofit Efficiency Index allows a combined evaluation of the strength and ductility improvements.

The study does not propose new modelling techniques; instead, its value resides in the systematic synthesis of empirical data across three structural typologies under uniform analytical assumptions. This enables the comparison of types, thus providing a more transparent basis for engineering judgement in post-earthquake decision-making regarding assessment and retrofit prioritization.

The ranges proposed are based on low, to mid-rise buildings similar to those in this study; applying them to taller or more irregular typologies should involve engineering judgement. Also note that the analyses were performed using nonlinear static procedures though consistent for comparison, future research could extend the framework with further case studies, explicit treatment of uncertainty, and nonlinear dynamic analysis of representative typologies.

Overall, the results demonstrate that meaningful comparison between URM, CM, and RC buildings is possible within a coherent performance-based framework. The integrated guidelines developed in this study contribute to bridging empirical post-earthquake evidence with practical retrofit decision-making.

LIMITATIONS AND FUTURE RESEARCH

The suggested ranges are optimized for low to mid-rise buildings as they are representative of the study set. Use on taller or more irregular structures is advised with caution. Furthermore, the framework is based on nonlinear static procedures, which provide consistent comparative results but do not capture record-to-record variability or higher-mode effects. Further extensions could, for example, include further case studies and particularly more dynamic simulations to improve the proposed benchmarks.

AUTHOR CONTRIBUTION

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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