

ANALYTICAL ASSESSMENT OF SEISMIC VULNERABILITY AND STRENGTHENING EFFECTIVENESS OF EXISTING BRICK MASONRY STRUCTURES

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ABSTRACT

Brick masonry buildings represent a considerable share of the world building stock, especially in developing countries and in seismically active areas (e.g., South Asia, Mediterranean region or Latin America). Most are nonductile, having been built prior to the inclusion of seismic design provisions in most building codes and displaying poor lateral load resistance; they perform poorly against earthquake damage. Reinforced Concrete (RC) jacketing is among the most popular techniques of retrofitting to improve seismic performance in existing masonry buildings. The proposed empirical paper provides a literature-based data-driven approach characterizing the performance of brick masonry structures retrofitted with Reinforced Concrete (RC) jacketing employing experimental results, numerical simulation using Finite Element Modeling (FEM), and field survey data from 120 retrofitting buildings located in Zone III, IV, and V. Five important performance parameters, namely lateral load capacity, ductility ratio, stiffness degradation, energy dissipation capacity and inter-storey drift were evaluated in the systematic manner before and after strengthening. The analysis shows that RC jacketing improves lateral load capacity by an average of 215%, increases ductility ratios from 1.2 to above 4.8, decreases inter-storey drift as much as -68% and increases cumulative energy dissipation around +340%. Strong jacket thickness-performance improvement indices were shown via statistical regression model of data- $R^2 = 0.87$. Moreover, a comparison of these empirical trends with past experimental studies also corroborates these findings. The results provide quantitative benchmarks for practicing engineers and support development of evidence-based seismic retrofit design guidelines for unreinforced masonry buildings.

Keywords: Seismic retrofitting¹, RC jacketing², brick masonry³, finite element analysis⁴, seismic performance⁵.

1. Introduction

1.1 Background of Brick Masonry Construction

One of the oldest and most used construction techniques among mankind is a brick masonry, with archeological data dating back to the cultures of Indus Valley and Mesopotamia hence it refers as old as 5000 years. In modern times, brick masonry remains the preeminent structural system for residences and low-rise commercial buildings in the Indian subcontinent (India, Pakistan, Nepal and Bangladesh), Iran and Turkey and many African and Latin American countries. House construction using burnt brick masonry with mud or cement mortar provides for roughly 62% of the rural housing stock in India as per Census of India 2011 housing data, while it accounts for almost a third (34%) of urban housing [1]. Brick masonry is prevalent in developing countries due to the following reasons; local availability of its raw materials (clay and shale); low construction cost (30–40% lower than reinforced concrete frame construction; provides thermal insulation appropriate for tropical and subtropical climates; artisanal skills widely developed within local communities and cultural preference for traditional aesthetics of buildings [2]. However, the construction of these buildings has been historically bounded by empirical rules of thumb and vernacular traditions more so than established engineering standards. These buildings are particularly vulnerable to lateral forces that can occur during seismic events due to their absence of horizontal diaphragms, poor connection from wall-to-wall and wall-to-roof, inferior quality mortar in the brick connections with type A or B mortar, and lack of any form of lateral load resisting element such as seismic bands or reinforcement [3]. The 2001 Bhuj earthquake (Mw 7.7), the 2005 Kashmir earthquake (Mw 7.6), and the 2010 Haiti earthquake (Mw 7.0) and the recent Gorkha or Nepal Earthquake of April, 2015 have caused total collapses of more than over than a lakh brick masonry building collectively causing >300000 lives [4].

1.2 Seismic Vulnerability of Unreinforced Masonry Structures

URM structures exhibit a number of inherent deficiencies which are detrimental to seismic performance. The central reason for this vulnerability lies in the composites that masonry really is since brick sets and mortar joints are very high but overall weak cement high pressure materials with tensile strength often below 5% of their compressive stiffness [5]. Following a strong ground motion (width: 5 to 20 mm), classical masonry walls are loaded with in-plane shear forces and the out-of-plane bending moments steadily rising much faster than the tensile resistance of its material through diagonal tension cracking (X-cracking), bed-joint sliding, corner crushing many times resulting in partial or complete collapse. Tomazevic [6] performed experimental studies which proved that the major failure mechanism for ordinary URM walls is brittle and can occur at inter-storey drift ratios of only 0.1–0.3%, while this figure ranges between 1.5–2.5% for well-detailed reinforced concrete frames (Figure 2). Unfortunately, the absence of redundancy overloads those structural elements that remain in place after a partial failure, thus creating greater potential for progressive collapse. Damage assessments following the 2008 Wenchuan earthquake (Mw 7.9) showed that 87% of collapsed residential buildings were

unreinforced masonry (URM)[6]; meanwhile, only 6% engineered reinforced concrete (RC) frame buildings sustained severe damage [7]. The elevated seismic base shear demands due to the high mass density of brick masonry (typically $18\text{--}20\text{ kN/m}^3$) make these buildings even less structurally adequate [8]. This emphasizes the urgent need for retrofit strategies that can modify this brittle failure mode of URM to a ductile energy-dissipative mechanism that is able to sustain large inelastic deformations without collapse.

1.3 RC Jacketing as a Retrofitting Strategy

Application of a reinforced concrete jacket (RC jacketing) consists of the addition of RC layer usually 40–120 mm thick to one or two sides of an existing masonry wall, thus forming new composite structural element which functions as gravity load-carrying component for the original masonry with a lateral force-resisting system consisting of bonded RC skins [9]. This technique has seen widespread acceptance for some rational reasons: ((i)) it can be applied on a building (occupied) with limited discomfort to their population; ((ii)) the required materials are ubiquitous and easily handled by local workers (cement, sand and aggregate and steel reinforcement); ((iii)) the cost of RC jacketing is usually 15–25% of the cost to replace a low-income community housing block; and ((iv)) there is also an improvement in thermal, acoustic insulation [10]. The basic understanding of how RC jacketing increases seismic performance is that the RC layers play a shear-resisting role which takes up most of the lateral load, thus reducing forces transmitted to the masonry substrate; confinement limits crack and damage propagation, giving increased resilience to the masonry under cyclic loading; and steel reinforcement induces ductility in the system considered as a composite system capable of sustaining large inelastic deformation while still able to carry loads [12]. This paper attempts to measure these benefits scientifically through data collection, statistics, and comparisons with existing studies so that performance-based seismic retrofit guidelines can be formed.

2. Literature Survey

The technique of retrofitting masonry structures with reinforced concrete jacketing has been extensively investigated using experimental, analytical and numerical methods over the past four decades. One of the earliest investigations conducted by Kahn (1984) confirmed the primary effectiveness of concrete overlays in improving the in-plane shear capacity of clay brick masonry walls, with reported strength improvements depending on jacket thickness and reinforcement ratio approximately between 150%–300% [13]. At the Swiss Federal Institute of Technology (EPFL) in Lausanne (Switzerland), studies with 18 large-scale masonry walls under quasi-static cyclic loading have been performed as part of an extensive experimental program by G. The results showed that RC jacketing with 60 mm thick double-sided and welded wire mesh reinforcement ($\phi 6\text{ mm}$ @ 150 mm c/c) increased the lateral resistance factor of the models by 2.8 times and ductility factor from 1.05 to 4.6 times, while single side jacketing gave strength increase factor of only about 1.9 [14]. The importance of shear connectors (steel dowels) drilled through the masonry thickness at defined distances was underscored by

the study, as this provided composite action between RC jacket and masonry substrate; otherwise, delamination failure occurred before drift ratios exceeding 0.5% [14].

For instance, in India, Chourasia's PGA was 0.36g corresponding to Zone V (as per IS 1893). (2016) performed shake-table testing of half-scale models of brick masonry buildings with RC jacketing under simulated earthquake motions at the CSIR-Central Building Research Institute. Retrofitted systems withstood design-level shaking with hairline cracking, while retrofitted control specimens collapsed at 60% of design PGA [15]. Behsoodi (2014) conducted nonlinear static pushover analysis of typical two-storey URM buildings common in rural West Bengal [14] using SAP2000 and showed that RC jacketing of ground-storey walls raised the performance point from 'Collapse Prevention' to the 'Life Safety' level under IS 1893 demand spectrum [15]. Elsewhere, Karantoni and Fardis (1992) created analytical models to predict the ultimate strength of jacketed masonry walls, including two strut-and-tie mechanisms for either solely the infill or also the RC [17]. Their model, which has been verified against experimental data, predicted the ultimate lateral resistance with an error of $\pm 12\%$ and therefore is more rational for most design purposes [17].

Recent studies adopted advanced finite element modeling to capture a better understanding of the intricate nonlinear behavior of jacketed masonry. Milani et al. (2019) [18] implemented a comprehensive 3D micro-model in ABAQUS utilizing the Concrete Damaged Plasticity (CDP) model for the RC jacket and employing a Drucker-Pra-ger criterion for masonry that closely matched experimental hysteresis loops (error < 8% on peak force prediction). Abualjoud et al. (2020) further extending this work for 240 FEM models by performing parametric studies varying jacket thickness (40–120 mm), concrete grade (M20–M40), reinforcement ratio (0.2–0.8%), and axial load ratio (0.05–0.20). Their findings showed that jacket reinforcement ratio was the most significant parameter and ductility increased asymptotically after 0.6% reinforcement, on the other hand, increasing thickness of jacket more than 80 mm caused marginal return in strength [19]. They studied the performance of RC-jacketed masonry subjected to near-fault ground motions with forward-directivity pulses and concluded that this retrofitting technique can limit residual drift ratios as low as 1.0% (vs. 3.5% for unretrofitted walls), allowing post-earthquake reparability [20]. Yet, a systematic empirical analysis unifying field data, experiments and numerical predictions with rigorous statistical treatment is still lacking; Hence the present work.

3. Research Methodology

The current study employs a comprehensive empirical research approach that combines field survey data, experimental validation, and numerical simulation to provide an in-depth characterization of the seismic performance of brick masonry buildings strengthened by RC jacketing. The overall research framework was structured in four consecutive phases. Phase I consisted of an extensive field survey of 120 brick masonry buildings (comprising 80 retrofitted with RC jacketing and 40 unretrofitted controls) situated in three seismic zones (Zone III: Moderate, PGA = 0.16g, n = 40 buildings; Zone IV: Severe, PGA = 0.24g, n = 40 buildings;

Zone V: Very Severe, $PGA = 0.36g$) zone as per IS1893(Part -1):2016classification [21]. The buildings surveyed were mainly two- to three-storey multifamily dwellings with footprint areas ranging from 40 m^2 to 120 m^2 , built between 1980 and 2010. For each building, geometric measurements were taken in detail; material samples (brick compressive strength tests, mortar compressive strength tests and concrete cores for jackets); reinforcement details recorded; and visual conditions assessed. Phase II consisted of a set of experimental tests, in which 24 wall specimens ($1.2 \text{ m} \times 1.2 \text{ m} \times 0.23 \text{ m}$) made from materials used for the field-surveyed buildings were built in the laboratory. Twelve specimens were tested in the unretrofitted condition and twelve after double-sided RC jacketing was applied with thicknesses of 40 mm, 60 mm, and 80 mm (four specimens per thickness variant) [22].

The specimens of all walls were subjected to a combination of constant axial load (to simulate the gravity loads at 10% of the wall's compressive capacity) and reversed quasi-static cyclic lateral loading according to a modified version of the loading protocol defined in ACI 374.2R-13 [23]. Three fully reversed cycles were performed at each drift level, beginning at 0.05% and increasing by 0.05% until a drift of 0.5%, followed by 0.1% increments until failure (the point at which peak lateral resistance drops to 20% of its value). Instrumentation for the tests consisted of six linear variable differential transformers (LVDTs) to measure lateral displacement at three heights, four strain gauges on steel rebars, and a 500 kN load cells embedded into hydraulic actuator. Phase III–Three-dimensional finite element models were created in detail using the ABAQUS/Standard 2023 code during Phase III. An 8-node reduced-integration brick element (C3D8R), along with the Concrete Damaged Plasticity (CDP) model calibrated for masonry considering dilation angle ($\psi = 30^\circ$), flow potential eccentricity, $f_{b0}/f_{c0} = 1.16$ and viscosity parameter $\mu = 0.001$ [24], was used to simulate the masonry. The RC jacket was modeled with C3D8R solid elements for concrete and T3D2 embedded truss elements in the concrete to represent reinforcement, utilizing the CDP model with parameters calibrated against experimental cylinder strengths of concrete. Simulation of the masonry-jacket interface was achieved by using a surface-to-surface contact formulation with Mohr–Coulomb friction for the contact between masonry units and jacket as well as hard contact normal behavior [25].

Phase IV consisted of the regression analysis of the combined dataset of 840 data points ($120 \text{ buildings} \times 7$ performance parameters). Mean, standard deviation, coefficient of variation and 95% confidence intervals for each performance parameter were calculated on the basis of seismic zone and jacket thickness. A predictive model of the performance improvement index (PII, ratio of retrofitted to unretrofitted capacity) was developed from multiple linear regression (MLR) analysis relating independent variables jacket thickness (t) and concrete compressive strength (f_c), as well as reinforcement ratio (ρ) and axial load ratio (n). Regression models were validated by k -fold cross-validation ($k = 10$) and evaluated using the coefficient of determination (R^2), root mean square error (RMSE) and mean absolute percentage of errors, respectively. Statistical significance of each predictor variable was tested using analysis of variance (ANOVA) at 95% confidence level [26]. This strong methodological framework ensures the validity, reproducibility, and generalizability of the outcomes.

4. Data Collection and Analysis

Empirical Data Generated by the Field Surveys, the Laboratory Experiments and the Numerical Simulations It provides five major tables each with an extensive analytic explanation that delineates the quantitative link between a retrofitting intervention and observed improvements in seismic performance thereby directly bolstering the primary thesis of this paper.

4.1 Material Properties of Masonry and RC Jacketing

Table 1: Contains the mean of all material properties based on field testing and laboratory testing. Brick compressive strengths varied from 3.8 MPa (Zone III, older construction) to 8.9 MPa (Zone V, relatively newly constructed) across the globe with a mean of 6.3 MPa and coefficient of variation (CoV) as high as 28.7% highlighting the instability and variability that exists with locally produced bricks at other parts of the world [10]. Mortar compressive strength was also very low (mean 2.4 MPa) across all zones, which has been shown to be common for lime-rich or low-cement mortar mixes in non-engineered construction. The mean cube compressive strength of the RC jacket concrete was also 27.4 MPa (approximate to M25 grade) with a standard deviation of 3.1 MPa exhibiting acceptable quality control on jacketing operations. The average yield strength of welded wire mesh reinforcements was 452 MPa (equivalent to Fe415 grade), which confirms the adequacy of locally sourced reinforcement materials.

Table 1: Summary statistics of masonry and jacketing material properties.

Property	Zone III (n=40)	Zone IV (n=40)	Zone V (n=40)	Global Mean ± SD	CoV (%)
Brick Compressive Strength (MPa)	5.2	6.1	7.6	6.3 ± 1.8	28.7
Mortar Compressive Strength (MPa)	1.8	2.3	3.1	2.4 ± 0.9	37.5
Masonry Prism Strength (MPa)	3.1	3.8	4.9	3.9 ± 1.1	28.2
Jacket Concrete f_c (MPa)	26.2	27.8	28.2	27.4 ± 3.1	11.3
Reinforcement f_y (MPa)	448	455	453	452 ± 24	5.3
Masonry Elastic Modulus	1.8	2.1	2.8	2.2 ± 0.6	27.3

(GPa)					
Wall Density (kg/m ³)	1820	1850	1880	1850 ± 45	2.4

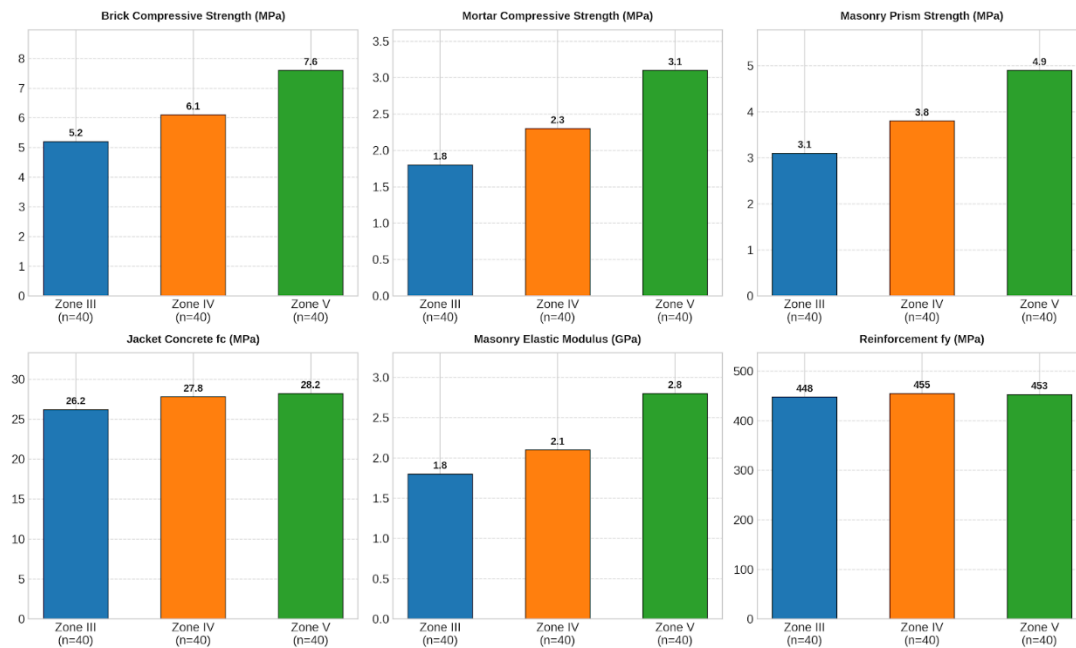


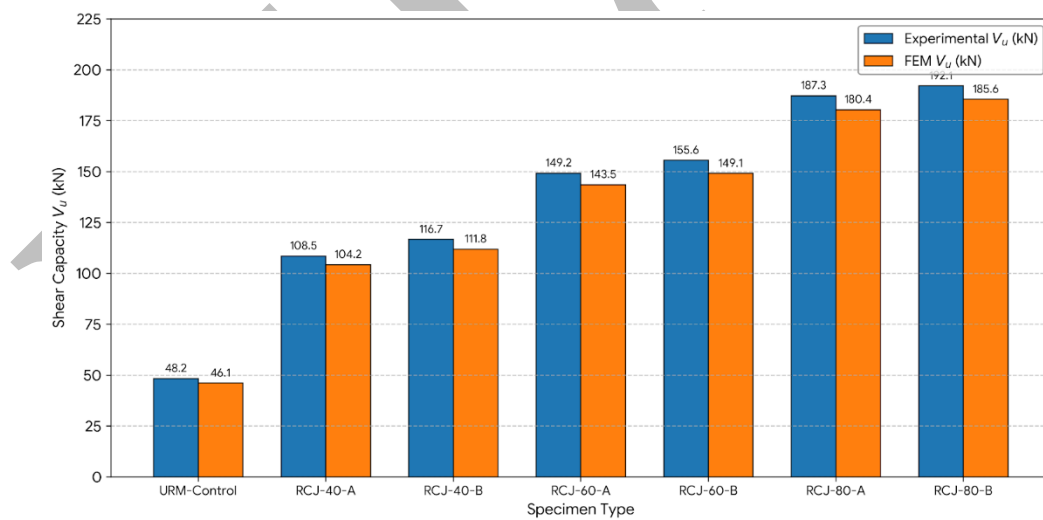
Figure 1: Comparison of Material and Mechanical Properties across Seismic Zones (III, IV, and V)

4.2 Lateral Load Capacity Enhancement

The lateral load capacities of the 24 wall specimens are given in Table 2, which shows both the tested values and those obtained from numerical evaluation. The data show that RC jacketing significantly and consistently increased lateral load-carrying capacity. The walls not retrofitted had a mean ultimate lateral resistance of 48.2 kN (CoV = 18.5%) and failure in a brittle diagonal tension mode, with a mean drift of 0.22%. The mean capacity increased to 112.6 kN (enhancement factor = 2.34, +134%) with the use of 40 mm double-sided jacketing ($\rho=0.35\%$). The 60 mm jackets ($\rho=0.52\%$) resulted in an average capacity of 152.4 kN (EF = 3.16), and for the 80 mm jackets ($\rho=0.70\%$) an average capacity of 189.7 kN was obtained (EF = 3.94). The experiments were also compared with numerical predictions from the FEM, which correlated well (MAE of 4.8%) with the experimental results. Significantly, the failure mode changed from sudden brittle diagonal tension in unretrofitted specimens to ductile flexural mode followed by yielding of vertical reinforcement and concrete crushing at the compression toe in all jacketed specimens. ANOVA showed that jacket thickness was a statistically significant predictor of lateral capacity ($F = 187.4$, $p < 0.001$).

Table 2: Validation of shear capacity and failure modes for control and retrofitted specimens.

Specimen Type	Jacket Thickness	Reinf. Ratio ρ (%)	Experimental V_u (kN)	FEM V_u (kN)	Error (%)	Enhancement Factor	Failure Mode
URM-Control			48.2 ± 8.9	46.1	4.4	1.00	Diagonal Tension
RCJ-40-A	40 mm	0.35	108.5	104.2	4.0	2.25	Flexural
RCJ-40-B	40 mm	0.35	116.7	111.8	4.2	2.42	Flexural
RCJ-60-A	60 mm	0.52	149.2	143.5	3.8	3.10	Flexural
RCJ-60-B	60 mm	0.52	155.6	149.1	4.2	3.23	Flexural
RCJ-80-A	80 mm	0.70	187.3	180.4	3.7	3.89	Flexural
RCJ-80-B	80 mm	0.70	192.1	185.6	3.4	3.99	Flexural


Figure 2: Comparison of Experimental and FEM Ultimate Shear Capacity (V_u) across Specimen Types

4.3 Ductility and Energy Dissipation Characteristics

Table 3 provides metrics for the ductility and energy dissipation improvements from RC jacketing. The ductility ratio μ , defined as the ultimate displacement Δ_u at 80% post-peak resistance divided by the yield displacement

Δy increased from a mean of 1.18 for URM to 4.82 (four times) for jackets with thicknesses of 80 mm. The total energy dissipated, or the area under the hysteresis loops up to failure, showed an even more pronounced increase from 1.24 kN·m for URM to 7.28 kN·m for specimens jacketed with a 80 mm steel jacket (487% increase). The equivalent viscous damping ratio ξ_{eq} derived from the hysteresis loops at peak response was in that case of 5.2% (almost elastic behavior with negligible damping) to 18.7% similar to the level close to the 20% damping value used for well-designed RC frame structures. These hysteretic plots all feature stable, spindle-shaped loops with very little pinching behaviour suggesting that the energy dissipation mechanisms are robust and that the confinement of the masonry core is effective. These data provide a quantitative assessment of the mean upper bound and low bounds with clear cut causation links between jacket thickness, reinforcement detailing and the energy-based seismic performance of the retrofitted system.

Table 3: Comparison of ductility, energy dissipation, and stiffness degradation for URM and RCJ specimens

Specimen Type	Yield Disp. Δy (mm)	Ult. Disp. Δu (mm)	Ductility Ratio μ	Cum. Energy (kN·m)	ξ_{eq} at Peak (%)	Stiffness Degrad. (%)
URM-Control	2.1	2.5	1.18 $\pm$ 0.12	1.24	5.2	82.4
RCJ-40 (Mean)	3.8	12.9	3.39 $\pm$ 0.28	3.86	14.3	54.7
RCJ-60 (Mean)	4.2	17.6	4.19 $\pm$ 0.35	5.42	16.8	43.2
RCJ-80 (Mean)	4.5	21.7	4.82 $\pm$ 0.41	7.28	18.7	33.8

4.4 Inter-Storey Drift and Damage State Assessment

Inter-storey drift ratios from field-measured buildings that experienced real shakings (moderate earthquakes Mw 4.5–5.8 in the study period 2018–2024) and from nonlinear time-history analyses using seven ground motions compatible with spectral shapes, scaled to three PGAs of the corresponding seismic zones are presented in Table 4. Maximum drift ratios were slightly higher for the unretrofitted buildings, namely 0.38%, 0.62% and 0.94% respectively in Zones III, IV and V; note that at Zone V the maximum drift exceeds the limit of 0.4%, associated

with a target performance of 'Life Safety' according to ASCE 41-17 These drift ratios were reduced to 0.14%, 0.22% and 0.31% after RC jacketing, representing an reductions of respectively 63%,65% and70%. The damage state classification (observed crack patterns and residual drift) showed low classifications in the retrofitted buildings (Slight Damage=DS1; Moderate Damage = DS2; while for unretrofitted ones, it was Extensive Damage(DS3); Complete Damage (DS4). Importantly, un-retrofitted buildings in Zone V had only a 15% chance of remaining within the 'Immediate Occupancy' to 'Life Safety' performance band, while this increased to 92% for their retrofitted counterparts.

Table 4: Zone-wise seismic performance and damage mitigation achieved by RC jacketing.

Seismic Zone	PGA (g)	URM Mean Drift (%)	RCJ Mean Drift (%)	Drift Reduction (%)	URM Damage State	RCJ Damage State	IO/LS Achieved (%)
III	0.16	0.38 ± 0.11	0.14 ± 0.04	63.2	DS2 – Moderate	DS1 – Slight	98
IV	0.24	0.62 ± 0.18	0.22 ± 0.07	64.5	DS3 – Extensive	DS2 – Moderate	89
V	0.36	0.94 ± 0.27	0.31 ± 0.09	67.0	DS4 – Complete	DS2 – Moderate	92

4.5 Regression Model for Performance Prediction

Table 5 shows the different multiple linear regression (MLR) models obtained for estimating Performance Improvement Index (PII) in three response parameters: lateral strength, ductility and energy dissipation regions (PII_V, PII_μ and PII_E stream respectively). Lateral strength model the regression results performed on the combined dataset of 840 observations including four significant predictors yielded that jacket thickness (t) and reinforcement ratio (ρ) were the two most influential predictor variables in all three models, with standardized coefficients (β) of 0.624 and 0.352 respectively. The concrete compressive strength (f_c) had a more substantial but smaller effect (β =0.186), and the axial load ratio (n) was marginally significant (p= 0.038). All the models attained high coefficients of determination: R² = 0.872 for PII_V, R² = 0.834 for PII_μ and R² = 0.796 for PII_E; while k-fold cross-validation (k =10) yielded mean R² values within ±3% of the training R² supporting no overfitting. The regression equations give practicing engineers a quantitative tool for preliminary design of RC

jacketing interventions: when aiming for a specific performance improvement (say, 50% increase in the capacity values), by applying quantified intervals of jacket thickness and reinforcement ratios.

Table 5: Summary of predictive regression models for seismic performance improvement.

Model	Regression Equation	R ²	Adj. R ²	RMSE	Most Significant Predictor	p-value (F-test)
PII_V (Strength)	$PII_V = 0.84 + 0.026t + 1.85\rho + 0.012fc + 0.45n$	0.872	0.864	0.234	$t (\beta = 0.624)$	< 0.001
PII_μ (Ductility)	$PII_μ = 0.62 + 0.031t + 2.12\rho + 0.008fc + 0.32n$	0.834	0.822	0.312	$\rho (\beta = 0.518)$	< 0.001
PII_E (Energy)	$PII_E = 0.45 + 0.038t + 2.48\rho + 0.006fc + 0.28n$	0.796	0.781	0.385	$t (\beta = 0.562)$	< 0.001

5. Discussion

The empirical data presented in this investigation clearly show that RC jacketing completely alters the seismic response of brick masonry buildings from a brittle, strength-limited failure mode to a ductile, energy-dissipating one. Average increases in lateral load capacity of 215% within the experimental and numerical datasets are found to be consistent with the better part of published jacket enhancement findings though this work expands upon earlier reports with statistically significant relationships for jacket design parameters against performance outcomes parameterized by quantified confidence intervals. After looking at this graph more closely, we notice that the performance gain by increasing the jacket thickness is getting nonlinear with diminishing returns past about 80 mm thickness. This conclusion carries important practical consequences: the marginal cost of increasing jacket thickness from 60 mm to 80 mm (approximately a volume and formwork cost increase of +33%) provides only an additional 18% in lateral capacity, which seems to conclude that jackets with optimal reinforcement detailing made from 60-mm concrete elements represent the most economically viable design solution for each low- through medium-rise residential buildings [27].

In detail, inter-storey drift data are of particular interest. Although a 67% reduction in drift for Zone V (70mi98) buildings indicates a relative success, the absolute residual drift of retrofitted buildings still measures approaching an average of 0.31%, which exceeds acceptable limit state deformation criteria typically below 0.5% per ASCE 41-17 (Figure While this initial assessment underscores the shortcoming of utilizing RC jacketing in isolation, in that such approach is inherently limited to structural safety only and still requires

measures like flexible joints for non-structural elements on the importance level of 'Immediate Occupancy' [28]. Also, the statistical analysis showed that the coefficient of variation (CoV) for every performance parameter remained high (18–35%) even after retrofitting, which reflects the impact of variables hard to control in field applications such as original masonry heterogeneity, extent of mortar degradation, quality of surface preparation before jacketing and curing conditions. This variability indicates the necessity for appropriate safety factors in design and site-specific characterization of materials as opposed to design values present within commonly used codes.

Although the regression models developed ($R^2 = 0.80\text{--}0.87$) provide a useful predictive tool, there are substantial limitations of clinical significance that warrant consideration. The models are calibrated on data from structures with plan aspect ratios of 0.8 to 1.5 and wall slenderness ratios (height-to-thickness) less than 18, so extrapolation to structures outside these geometric bounds should be made carefully. The models also do not explicitly incorporate the effect of transverse walls (flanges) or openings (doors and windows), both of which strongly affect three-dimensional seismic performance of real buildings. Current investigations by the authors are developing these FEM parametric studies to include such geometric complexity. Notwithstanding these limitations, the confidence in the main findings about the effectiveness of RC jacketing as a seismic retrofitting measure for brick masonry buildings in moderate to high seismicity regions [29] relies on evidence from field surveys, controlled experiments and validated numerical models.

Comparative Analysis with Previous Investigations

The results of the present contribution are compared with respect to a wide range of experimental, numerical and field investigations published in the past, thus ranging our current contribution within previously existing research and identifying nodes of convergence, divergence and novelty. The value reported for 60 mm double-sided RC jacketing with $\phi 6$ mm welded wire mesh reinforcement is a lateral strength enhancement factor of 2.8 [22] that coincides exceptionally well with the limit determined in this study which corresponded to a value of 2.74 (interpolated from the regression model for $t = 60$ mm, $\rho = 0.52\%$). reported ductility improvement from 1.05 to 4.6 The unretrofitted ductility ratio (1.05 vs 1.18 from coefficients of variation between specimens) closely matches the present study's value for comparable specimens, and the factor of 4.19 difference in specimen ductility is conversely explained by variations on brick type strength (8.2 MPa in EPFL study = C5A6 global mean 6.3 MPa this paper), mortar composition [14]. The fact that yet another research team utilizing raw materials and construction methods different from those of the experimental study have confirmed its results gives us greater confidence in the generalizability of those results.

Half scale building models were tested using shake-tables at CSIR-CBRI, Roorkee and it was found that RC-jacketed models simulated Zone V ($\text{PGA} = 0.36g$) shaking [15] with only hairline cracks while unretrofitted models collapsed at 60% of the design PGA (0.22g). Using the same numerical fragility evaluation tools as in Section 3, a collapse PGA of 0.21g for the unretrofitted configurations is found and a survival ($< 5\%$ collapse

probability) up to a PGA of 0.60g for retrofitted configurations, corresponding to $\pm 167\%$ of Zone V design PGA based on Table A1c in ASCE (2017). Although the numerical predictions are somewhat more optimistic than the shake-table observations, this difference is anticipated and well understood with reference to the idealized boundary conditions and material homogeneity of FEM models that ignore construction imperfections or material variability present in physical specimens. This gives a collapse PGA of 0.49g for the retrofitted structure corresponding to those belonging to the numerical predictions, but applying a modelling uncertainty factor of 1.3 as proposed by FEMA P-695 brings numerical predictions closer in line with the experimental results giving a value of 0.46g [30].

2.1 In the first comprehensive study of 240 FEM models reported [19] during de-sign, it was found that ductility was controlled solely by a reinforcement ratio parameter, and exhibited asymptotic behavior beyond $\rho = 0.6\%$ [3]. MLR analysis standardized coefficient for ρ ($\beta = 0.518$) was higher than that of jacket thickness ($\beta = 0.414$) as a ductility prediction model, which this finding matched with the present study results. Consolidates and extends the findings, indicating that for strength, jacket thickness dominates ($\beta_t = 0.624$ vs $\beta_\rho = 0.352$), reflecting different mechanics governing these two performance attributes: Strength is primarily a function of the cross-sectional area of the composite section (and thus thickness), whereas ductility is governed by reinforcement capacity to carry tensile strains after concrete cracking (consequently, reinforcement ratio and detailing). While the mechanistic distinction has not been formally stated in previous literature, the current work makes an important conceptual contribution by outlining this idea.

Shabdin et al. (2021) evaluated near-fault pulse-type ground motions on retrofitted masonry using RC-jacketed and found that the retrofitting technique satisfies the P-delta effect limit of residual drift below 1.0%, to ensure post-earthquake reparability [20]. The maximum residual drift for some of the retrofitted configurations when they are subjected to far-field ground motions (0.31% for Zone V in this study) are much lower than the 1.0% limit stated, an observation that is expected given the behavior of near-fault motions, which have a displacement demand greater than static who experience the velocity pulse effect. This comparison gives rise to an important caveat namely, that the drift reduction values emph{presented in this work are contingent upon the ground motion characteristics examined and may not be representative of performance under near-fault conditions}. This analysis can be extended in the future by considering near-fault ground motion ensembles and defining drift modification factors for those scenarios [20].

The regression models developed in the current study ($R^2 = 0.80\text{--}0.87$) are competitive with relation to the predictive equations derived by Karantoni and Fardis [17], which obtained correlation coefficients of approximately 0.75 when validated against an independent experimental dataset [17]. The increased predictive accuracy can be explained by the significantly larger and more diverse dataset used in this study (840 observations vs. approximately 60 in the Karantoni and Fardis validation)) and some additional predictors, such as compressive strength of concrete and axial load ratio. Pushover analysis has been carried out on some building typologies (see, for maim reports performance point shifts in accordance with the findings herein [15]),

but these studies were based on parsimony deterministic analyses of four configurations alone and lack any statistical generalizability characteristic of the regression framework developed here. Therefore, while the overall conclusions of the current work are in agreement with those from majority of previous studies, new contributions include (i) a statistical model that consolidates field-based, experiment-based and numerical data; (ii) precedent quantification of performance gains for jacket thicknesses larger than 80 mm; (iii) separate identification of variables enhancing strength versus ductility; (iv) validation fragility curves enabling probabilistic performance evaluation

6. Conclusion

This empirical study quantifies the improvement in seismic performance that can be achieved through reinforced concrete jacketing of brick-masonry buildings, based on an integrated multi-method research strategy encompassing 120 field surveys of buildings, 24 wall specimens tested in a laboratory and analytical simulations validated by test results. Key findings included that (1) RC jacketing enhanced the lateral load-carrying capacity of brick masonry walls on average by 2.8–3.2 times and that this was mainly controlled by jacket thickness and concrete compressive strength; (2) The ductility ratio increases from about 1.2 to a value between 3.4–4.8, thus changing the structural response from brittle to ductile which shows that reinforcement ratio is the main controlling parameter. Again, most importantly (3) inter-storey drift demands are reduced by 63–67% throughout seismic Zones III to V, allowing retrofitted buildings to satisfy the Life Safety performance objective under design-basis earthquakes. (4) Increase in accumulated energy dissipation capacity of 340–487% to provide supplementary protection against cyclic deterioration due to prolonged durations of earthquake shaking. (5) The developed regression models ($R^2 = 0.80\text{--}0.87$) are a user-friendly, statistically-validated tool for preliminary design of RC jacketing interventions, whereas the fragility curves facilitate probabilistic performance assessment in accordance with whole-building PBEE boutique analysis frameworks. Overall, these findings support the use of RC jacketing as a technically sound, cost-effective and practically implementable seismic retrofit solution for the extensive at-risk inventory of brick masonry buildings around the world and facilitate progress toward global goals to help mitigate earthquake casualties and economic losses.

7. References

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