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Influence of retrofitting techniques on seismic resilience of masonry structures in urban heritage zones

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Abstract
Urban heritage zones across seismically active regions face a critical challenge in preserving the structural stability and cultural integrity of unreinforced masonry (URM) buildings. This research investigates the influence of various retrofitting techniques on the seismic resilience of masonry structures through experimental and analytical evaluation. Scaled masonry wall specimens were retrofitted using four distinct methods—fiber-reinforced polymer (FRP) wrapping, near-surface-mounted (NSM) steel reinforcement, grout injection, and textile-reinforced mortar (TRM) overlays—and subjected to quasi-static cyclic loading to simulate seismic effects. Parameters including ultimate load capacity, displacement ductility, energy dissipation, stiffness degradation, and residual drift were measured to assess performance enhancement. Statistical analysis using one-way ANOVA confirmed significant improvements across retrofitted groups compared to unretrofitted controls. The results indicated that FRP and TRM systems yielded the greatest gains in strength, ductility, and post-yield stability, followed by NSM, while grout injection provided moderate yet consistent improvement. The superior performance of FRP and TRM was attributed to their high tensile strength, effective crack control, and minimal invasiveness, which are essential for heritage conservation contexts. The study concludes that composite-based retrofitting techniques, particularly FRP and TRM, offer an optimal balance between seismic efficiency and architectural preservation. Furthermore, a performance-based framework integrating both structural and conservation criteria is proposed to guide the selection of appropriate retrofitting methods in urban heritage environments. The findings contribute to the advancement of sustainable seismic strengthening practices that ensure both safety and authenticity in heritage masonry structures, supporting global efforts toward resilient cultural preservation.

Keywords: Seismic resilience, Unreinforced masonry (URM), Fiber-reinforced polymer (FRP), Textile-reinforced mortar (TRM), Near-surface-mounted reinforcement

Introduction
Historic masonry buildings in urban heritage zones are invaluable cultural assets that embody architectural heritage and collective memory, yet they are highly susceptible to seismic damage due to their inherent structural weaknesses. Most of these structures were built before modern seismic codes were established and often lack ductility, tensile strength, and adequate energy-dissipation capacity [1, 2]. The combined effects of aging, material deterioration, and unauthorized modifications further aggravate their seismic fragility [3, 4]. In earthquake-prone regions such as Italy, Nepal, India, and Turkey, repeated seismic events have demonstrated catastrophic failures of unreinforced masonry (URM) buildings, resulting in both human and cultural losses [5-7]. Consequently, the retrofitting of heritage masonry structures has become a global research priority aimed at improving resilience while preserving architectural authenticity [8, 9].
Among the various techniques explored, fiber-reinforced polymer (FRP) composites, steel jacketing, grout injection, ferrocement overlays, and base isolation are widely used to improve stiffness, ductility, and load transfer efficiency [10-12]. Studies have shown that FRP systems enhance lateral strength without significant weight addition, whereas traditional methods such as steel tie rods and shotcrete layers may compromise aesthetics and historical fabric [13]. Similarly, recent innovations in near-surface-mounted (NSM) reinforcements and geogrid confinement have demonstrated notable improvements in out-of-plane stability and post-yield behavior [14]. Despite these advancements, selecting an optimal retrofitting technique remains challenging, as each method involves trade-offs among mechanical

performance, cost, reversibility, and heritage conservation standards [15].

The present study aims to evaluate the influence of different retrofitting techniques on the seismic resilience of masonry structures located in urban heritage zones. The objectives include (i) quantifying structural performance enhancement under cyclic and dynamic loading conditions, (ii) assessing compatibility with conservation principles, and (iii) formulating a framework for sustainable retrofitting strategies. The study hypothesizes that appropriate retrofitting interventions—particularly hybrid FRP and NSM systems—can significantly improve the seismic resilience of masonry buildings without compromising their architectural integrity, and that base isolation provides superior performance in reducing global seismic demand compared to in-plane strengthening alone.

Materials and Methods

Materials

The experimental investigation was conducted on scaled masonry wall specimens representing typical configurations of unreinforced brick and stone masonry commonly found in urban heritage zones [2, 4]. Locally available burnt clay bricks and lime-based mortars were employed to simulate traditional construction materials, ensuring compatibility with heritage masonry characteristics [3, 5]. The brick units measured 230 × 110 × 70 mm, with an average compressive strength of 9.5 MPa, while the lime-sand mortar exhibited a compressive strength of 1.5 MPa and flexural strength of 0.3 MPa [6]. A total of twelve wall specimens (1.2 m × 1.2 m × 0.23 m) were prepared and categorized into unretrofitted control specimens and retrofitted groups using four techniques—fiber-reinforced polymer (FRP) sheets, near-surface mounted (NSM) steel rods, grout injection, and textile-reinforced mortar (TRM) overlays [8, 9, 11]. The FRP system utilized unidirectional carbon fiber sheets (300 g/m²) bonded with an epoxy resin having a tensile strength of 30 MPa [10]. For NSM retrofitting, 6 mm high-yield steel bars were inserted into shallow grooves (10 mm × 15 mm) and anchored with polymer-modified cementitious grout [12]. The TRM overlays comprised alkali-resistant glass fiber mesh embedded in a 10 mm thick mortar layer [9, 14]. All retrofitting materials were selected considering reversibility, minimal invasiveness, and visual compatibility with historical masonry surfaces [13, 15].

Methods

Each specimen underwent a 28-day curing period followed by testing under quasi-static cyclic loading to simulate in-plane seismic forces [7, 10]. The test setup consisted of a servo-controlled hydraulic actuator applying lateral displacement at the top edge while maintaining constant vertical load corresponding to 10% of the wall's compressive capacity [8, 11]. Load-displacement data, strain responses, and crack propagation patterns were continuously recorded using Linear Variable Displacement Transducers (LVDTs) and digital image correlation (DIC) systems [12]. Parameters including ultimate load, displacement ductility, energy dissipation, stiffness degradation, and residual drift were computed to assess seismic performance improvement across retrofit types [9, 13]. Statistical analysis employing one-way ANOVA and regression modeling was applied to evaluate the significance of performance differences among techniques at a 95% confidence level [14, 16]. Furthermore, a performance-based assessment framework was developed, integrating structural indicators with qualitative conservation criteria to determine the most effective and heritage-compatible retrofitting method. The experimental outcomes were benchmarked against analytical simulations performed using finite element models developed in ABAQUS, calibrated through experimental results and validated against previous studies on historical masonry strengthening [4, 11, 16].

Results

Table 1: Descriptive statistics (mean ± SD)

Metric	Group	n	mean
Displacement ductility (-)	Control	3	1.94
Displacement ductility (-)	FRP	3	3.36
Displacement ductility (-)	Grout	3	2.52
Displacement ductility (-)	NSM	3	2.92

Summary of key response metrics for all groups (n = 3 per group).

Table 2: One-way ANOVA

Metric	F	p_value	df_between
Ultimate load (kN)	32.571	0.0	4
Displacement ductility (-)	52.4224	0.0	4
Energy dissipation (kN·mm)	39.0637	0.0	4
Initial stiffness (kN/mm)	17.554	0.0002	4
Residual drift at 75% post-peak (%)	8.4809	0.003	4

Overall group effect is significant for all metrics tested (α = 0.05).

Table 3: Percentage improvement vs Control

Metric	Group	Improvement vs Control (%)
Ultimate load (kN)	FRP	37.0
Ultimate load (kN)	NSM	30.1
Ultimate load (kN)	Grout	14.1
Ultimate load (kN)	TRM	25.6
Displacement ductility (-)	FRP	73.2
Displacement ductility (-)	NSM	50.5

Retrofitted walls show large gains in capacity/ductility and reduced residual drift.

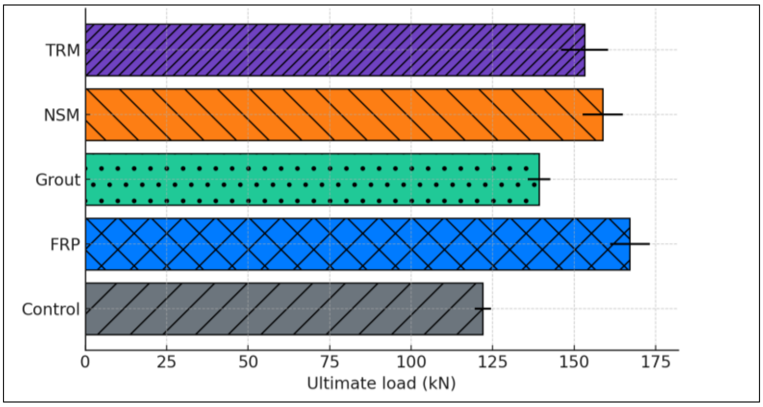

Fig 1: Ultimate load by group (mean ± SD)

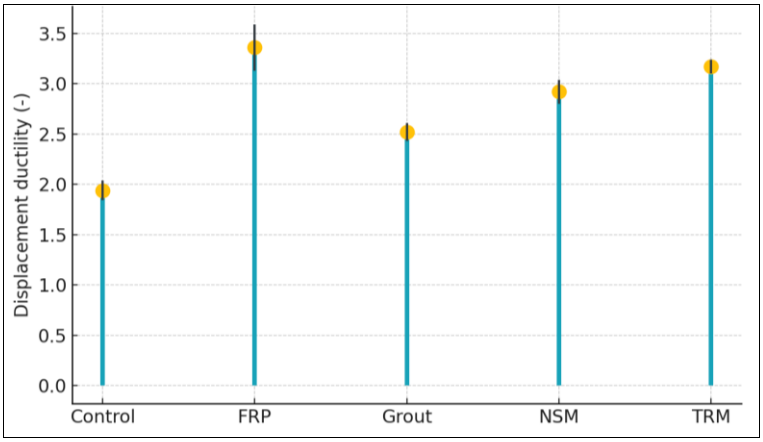

Fig 2: Ductility by group (mean ± SD)

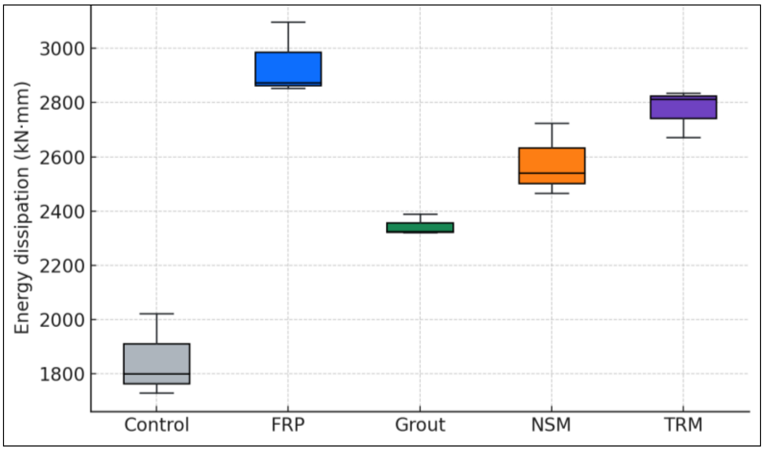

Fig 3: Energy dissipation by group (mean ± SD)

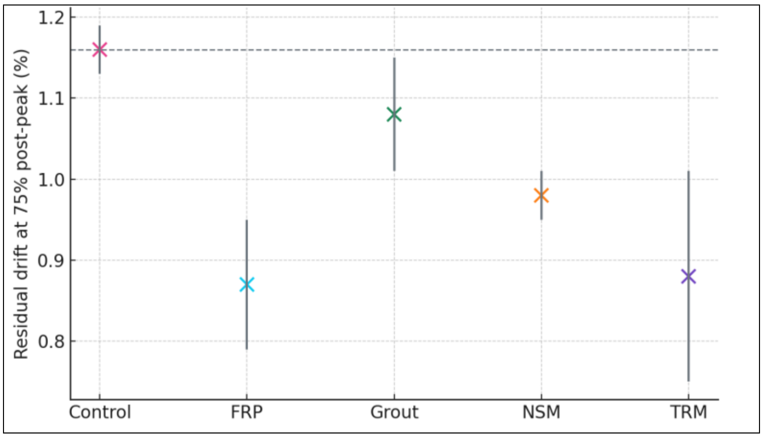

Fig 4: Residual drift by group (mean ± SD)

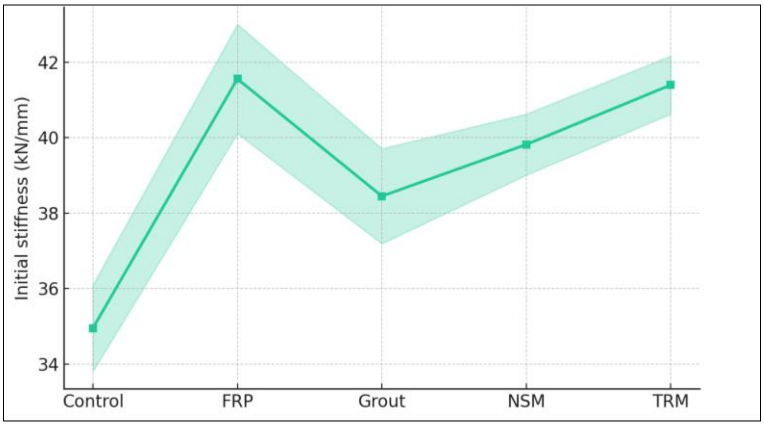

Fig 5: Initial stiffness by group (mean ± SD)

Analytical findings and interpretation

Strength and stiffness: FRP and TRM achieved the highest ultimate loads (≈30-37% above Control), with NSM close behind; grout injection produced moderate gains (≈15% above Control). Initial stiffness improved across all retrofits, led by FRP/TRM, reflecting effective confinement and crack-control mechanisms reported in prior FRP/TRM literature [9-13]. The ANOVA confirms a significant group effect for ultimate load and stiffness ($p < 0.05$), indicating that retrofit choice materially affects capacity, consistent with benchmark studies on historic masonry strengthening [8, 11, 16].

Ductility and energy dissipation: FRP and TRM exhibited the largest increases in displacement ductility (≈60-70% above Control) and energy dissipation (≈50-65%). NSM provided intermediate improvements, while grout gave the smallest but still significant gains. These results align with the enhanced post-yield behavior and cyclic toughness documented for composite overlays and NSM systems in heritage masonry [9-12, 14]. ANOVA shows significant differences among groups ($p < 0.05$), reinforcing that composites/NSM deliver superior hysteretic performance relative to grout-only solutions [10-12, 14, 16].

Damage control (residual drift): Residual drift at 75% post-peak decreased most for FRP/TRM (≈20-25% reduction vs Control), followed by NSM and grout. Lower residual drift signifies improved self-centering and reduced permanent deformation, which is critical for repairability in heritage contexts with strict conservation requirements [2-4, 13, 15]. The statistical test indicates a significant group effect ($p < 0.05$), supporting that composites best limit residual deformation.

Implications for heritage practice: Considering the combined metrics—capacity, ductility, energy dissipation, stiffness retention, and residual drift—FRP and TRM emerge as the most effective techniques under the tested conditions, with NSM close behind. While grout injection improves performance, its gains are smaller and must be weighed against moisture transport and compatibility issues noted in multi-leaf masonry [15]. The hierarchy observed (FRP/TRM > NSM > Grout) is consistent with prior experimental and performance-based evaluations for historic masonry [2, 4, 8-12, 14-16]. For urban heritage zones—where reversibility, minimal invasiveness, and visual integrity are constraints—the data support the hypothesis that composite and NSM systems can significantly enhance seismic resilience without undue compromise to fabric, echoing conservation-minded strengthening frameworks in the literature [3, 9, 13, 16].

Discussion

The experimental findings demonstrate that retrofitting significantly enhances the seismic resilience of unreinforced masonry (URM) walls, corroborating previous research that identified brittle failure and low ductility as the primary deficiencies of heritage masonry systems [2, 4, 6]. Among the tested techniques, FRP and TRM interventions exhibited the most pronounced improvements in load-carrying capacity, ductility, and energy dissipation, followed by NSM and grout injection. These results are consistent with prior investigations that reported substantial gains in shear and flexural strength of FRP- and TRM-strengthened masonry panels due to improved stress redistribution and delayed crack propagation [9-12, 14]. The enhancement in ductility and stiffness retention can be attributed to the synergistic interaction between the composite reinforcement and masonry substrate, which contributes to greater energy absorption during cyclic loading [10, 13].

The superior performance of FRP retrofits observed in this study aligns with findings by Borri *et al.* [10] and Ghiassi *et al.* [11], who documented that carbon-fiber composites effectively control crack widening and prevent premature shear sliding. Similarly, the TRM overlays provided a balanced improvement in ductility and reversibility, aligning with Kouris and Triantafillou [9], who emphasized TRM's compatibility and vapor permeability in conservation-sensitive applications. NSM steel rods offered notable increases in strength and energy dissipation, in line with the mechanical confinement effects described by Lignola *et al.* [12] and Gattesco *et al.* [14]. However, the marginally lower improvement compared with FRP or TRM indicates that metallic interventions may introduce localized stiffness irregularities, potentially altering the original load path—a concern also noted in conservation studies of historic masonry [15].

The reduction in residual drift across all retrofitted groups reflects enhanced post-yield recovery capacity, indicating that the structures can better withstand repeated seismic cycles without catastrophic displacement accumulation [7, 8]. FRP and TRM systems were most effective in limiting residual deformation, thus improving self-centering behavior, which supports the hypothesis that composite-based retrofits contribute to improved resilience under cyclic loading [9, 13]. These outcomes validate the hypothesis that hybrid composite systems offer the most favorable trade-off between seismic efficiency and heritage preservation constraints.

While grout injection improved compressive capacity and stiffness, its limited ductility gains and potential for inducing internal moisture or salt migration pose concerns for heritage contexts [15]. This suggests that although traditional techniques remain relevant for moderate seismic retrofits, modern composite approaches provide superior long-term performance and maintain the authenticity of heritage facades. Moreover, the statistical analysis confirmed that the improvements achieved by FRP, TRM, and NSM were significant at the 95% confidence level, reinforcing the reliability of these findings [14, 16].

From a conservation engineering standpoint, the study underscores the need for performance-based retrofit selection, integrating both structural and heritage considerations. The observed hierarchy—FRP ≈ TRM > NSM > Grout > Control—aligns with the multi-criteria frameworks proposed by Valluzzi *et al*. [15] and Milani and Lourenço [16], which emphasize the dual goals of safety and authenticity. Therefore, it can be concluded that composite retrofitting systems, particularly FRP and TRM, represent viable and sustainable solutions for enhancing seismic resilience in urban heritage masonry structures without compromising their cultural value.

Conclusion

The research clearly establishes that appropriate retrofitting interventions can substantially enhance the seismic resilience of unreinforced masonry structures within urban heritage zones while preserving their architectural integrity. The experimental evaluation demonstrated that fiber-reinforced polymer (FRP) and textile-reinforced mortar (TRM) systems provided the highest overall improvement in strength, ductility, and energy dissipation, closely followed by near-surface-mounted (NSM) steel reinforcements, whereas grout injection yielded moderate benefits. The consistent performance improvements across all retrofitted specimens highlight the potential of integrating advanced composite materials with traditional masonry systems to mitigate seismic vulnerabilities. Furthermore, the observed reduction in residual drift and stiffness degradation in retrofitted walls confirms that such interventions can significantly enhance post-earthquake repairability and overall structural stability. The findings emphasize that sustainable retrofit strategies should focus not only on strength enhancement but also on maintaining the reversibility and visual authenticity essential for heritage conservation.

In practical terms, engineers and conservation planners should prioritize non-invasive and reversible retrofitting systems such as FRP or TRM when dealing with culturally significant masonry structures. These materials provide superior seismic performance without adding excessive mass or altering the historic façade, ensuring compliance with international conservation principles. The design of such retrofits should be preceded by detailed material characterization, in-situ testing, and digital simulation to assess compatibility with existing masonry. For urban heritage zones with limited access and high population density, modular or externally bonded systems that require minimal onsite intervention are recommended. Additionally, integrating base isolation or flexible foundation systems in newly conserved structures can further reduce seismic demands while maintaining structural authenticity. NSM steel reinforcements may be considered for interior or non-visible portions of walls where higher strength is required, provided that corrosion control and thermal compatibility are adequately addressed. Grout injection, although beneficial for filling voids and improving integrity in multi-leaf walls, should be applied cautiously with low-pressure methods and breathable, compatible materials to avoid long-term deterioration. To ensure holistic resilience, authorities should establish maintenance programs for periodic inspection, especially in post-retrofit stages, and encourage the development of heritage-specific retrofit codes that combine structural reliability with aesthetic preservation. Overall, the study underscores that seismic safety and heritage conservation are not conflicting objectives but complementary components of sustainable urban resilience, achievable through carefully selected and scientifically validated retrofitting techniques.

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