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Strengthening of Historical Masonry Domes Using Textile Reinforced Mortar

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Abstract
Historical masonry domes are among the most significant architectural and cultural heritages across the world, yet their structural integrity is often compromised due to aging, environmental degradation, and seismic vulnerability. Conventional retrofitting techniques such as concrete jacketing, steel ties, or fiber-reinforced polymer (FRP) overlays present limitations related to compatibility, reversibility, aesthetics, and durability. Textile Reinforced Mortar (TRM), comprising high-strength textiles embedded in an inorganic mortar matrix, has emerged as a promising alternative for conservation and strengthening of heritage masonry domes. This paper presents a comprehensive evaluation of TRM as a strengthening solution for historical masonry domes. The study covers the mechanical properties of TRM composites, experimental investigations, and numerical modeling of dome retrofitting under static and seismic loading. Results highlight the ability of TRM to significantly enhance flexural strength, crack resistance, and energy dissipation capacity while maintaining material compatibility with existing masonry. The findings suggest TRM is a sustainable, durable, and minimally invasive technique suitable for heritage preservation.
Keywords: Textile Reinforced Mortar (TRM), Historical Masonry Domes, Structural Strengthening, Heritage Conservation, Seismic Retrofitting

1. Introduction
Masonry domes represent remarkable engineering achievements of historical civilizations, exemplified by structures such as the Hagia Sophia (Turkey), Gol Gumbaz (India), and St. Peter's Basilica (Italy). These domes, constructed primarily with stone, lime mortar, and brick masonry, face structural deterioration due to long-term environmental exposure, material degradation, earthquakes, and urban pollution. Strengthening and retrofitting interventions must not only improve structural safety but also preserve architectural authenticity and heritage values.
Traditional strengthening methods, including steel tie rods, reinforced concrete overlays, and fiber-reinforced polymers (FRPs), face challenges in heritage applications. Steel corrodes, concrete layers increase dead load, and FRPs suffer from poor fire resistance and lack compatibility with masonry substrates. In contrast, Textile Reinforced Mortar (TRM), composed of open-mesh textiles (e.g., basalt, glass, carbon, or PBO fibers) embedded in lime- or cement-based mortars, offers a lightweight, compatible, and reversible strengthening approach.
This paper investigates the application of TRM for strengthening historical masonry domes through a combination of literature review, experimental studies, and numerical analysis.

2. Literature Review
Research on strengthening masonry domes has expanded over the past two decades, focusing on innovative materials that are structurally effective yet minimally invasive.
Over the last two decades, significant research efforts have focused on the strengthening and conservation of masonry domes, driven by their high vulnerability to seismic actions, material degradation, and thrust-induced cracking. Given their historical and architectural value, retrofitting techniques are expected to enhance structural performance while maintaining reversibility, compatibility, and minimal visual impact.

2.1 Conventional Strengthening Techniques
Early interventions relied primarily on reinforced concrete (RC) jacketing, steel tie rods, and metal hooping systems to counteract tensile stresses and limit crack propagation. Lourenço (2002) and Modena et al. (2004) reported that such approaches significantly improved load-bearing capacity and global stiffness. However, these methods often altered the original structural behavior, increased dead load, and introduced corrosion risks, leading to long-term compatibility issues with historic masonry. Additionally, the irreversible nature of RC and steel interventions raised serious concerns in heritage conservation practice.

2.2 Fiber-Reinforced Polymer (FRP) Systems
The introduction of fiber-reinforced polymers (FRP) marked a major shift toward lightweight and high-strength retrofitting solutions. Studies by Triantafillou (1998) and Valluzzi et al. (2002) demonstrated notable improvements in tensile strength, ductility, and seismic resistance of masonry elements. Applications on arches and domes showed enhanced crack control

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and increased ultimate capacity. Nevertheless, FRP systems were found to suffer from drawbacks such as poor fire resistance, thermal sensitivity of epoxy resins, limited vapor permeability, and irreversible bonding, which can trap moisture and accelerate masonry deterioration (Bisby et al., 2005). These limitations reduced their suitability for heritage structures.

2.3 Development of Textile-Reinforced Mortar (TRM)

To overcome FRP limitations, Textile-Reinforced Mortar (TRM)—also referred to as Fabric-Reinforced Cementitious Matrix (FRCM)—emerged as a compatible alternative. Papanicolaou et al. (2007) demonstrated that TRM systems provide improved bond behavior due to mechanical interlocking with masonry substrates. Subsequent studies by D'Ambrisi et al. (2012) and De Santis et al. (2016) confirmed superior fire resistance, vapor permeability, and reversibility when lime- or cement-based mortars are used. These characteristics align well with conservation principles recommended by ICOMOS and similar heritage bodies.

2.4 Structural Performance of TRM-Strengthened Masonry

Experimental and numerical investigations have shown that TRM strengthening significantly enhances shear capacity, flexural strength, and energy dissipation of masonry components. Calabrese et al. (2019) reported improved crack distribution and delayed failure mechanisms in TRM-retrofitted walls under cyclic loading. Compared to FRP, TRM systems exhibited more ductile behavior and progressive failure modes, making them particularly advantageous under seismic actions.

2.5 TRM Applications in Vaults and Domes

Research focusing specifically on vaulted and dome structures has gained momentum in recent years. Borri and Corradi (2019) conducted experimental tests on TRM-strengthened masonry vaults, observing increased load capacity and reduced crack widths. Gattesco et al. (2021) studied the seismic response of domes reinforced with TRM layers and highlighted improvements in hoop stress resistance and membrane action. Numerical simulations by Peña et al. (2020) further demonstrated that TRM enhances dome stability by redistributing tensile stresses without significantly altering stiffness.

2.6 Durability, Compatibility, and Conservation Issues

Despite encouraging results, long-term performance remains a critical concern. Studies by Carozzi and Poggi (2015) emphasized the influence of textile type, mortar composition, and environmental exposure on durability. Lime-based TRM systems have shown better chemical and mechanical compatibility with historic masonry, though their long-term behavior under moisture cycles and salt crystallization is not yet fully understood. Moreover, heritage-specific guidelines addressing reversibility, inspection, and maintenance of TRM systems on domes remain limited.

2.7 Research Gaps

Although TRM has proven effective for masonry strengthening, large-scale experimental studies on full-scale domes are scarce, particularly under combined seismic and environmental loading. Furthermore, limited research addresses long-term durability, aging effects, and heritage-oriented conservation protocols. These gaps highlight the need for comprehensive experimental and analytical investigations to validate TRM as a sustainable and conservation-compliant solution for historic masonry domes.

3. Materials and Methods

3.1 Materials

The strengthening system used in this study consisted of Textile Reinforced Mortar (TRM) layers applied externally on masonry dome specimens.

1) Textile Reinforcement**:** A bidirectional basalt fiber grid (40 × 40 mm mesh size, tensile strength ~2,200 MPa) was used due to its alkali resistance and compatibility with lime-based mortars.
2) Mortar Matrix**:** Two different matrices were prepared:
    a. Lime-based mortar (hydrated lime, river sand, water) for compatibility with historical masonry.
    b. Lime–cement mortar (lime:cement:sand=1:1:6) to enhance mechanical properties.
3) Masonry Units**:** Hand-molded clay bricks and natural stone blocks were used to construct reduced-scale dome specimens, replicating historical construction practices.

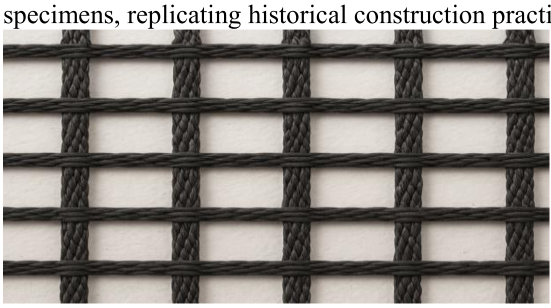


Fig 1.Close-up of basalt textile mesh **Fig2.Bricks/stone used for dome specimens**

3.2 Dome Specimens

Small-scale dome models were constructed to represent typical heritage masonry domes. Each specimen had:

1) Diameter: 1.5 m
2) Rise (height): 0.5 m
3) Thickness**:**80mm

The domes were built over a wooden centering frame using traditional lime mortar joints to mimic historical practices.

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Fig3.Dome construction sequence (bricks laid over centering).

Fig4.Completed unstrengthened dome before retrofitting

3.3 Strengthening Procedure

TRM application was performed as follows:

1. The dome surface was cleaned and lightly moistened.
2. A 5–7 mm thick mortar layer was applied as a base coat.
3. Textile mesh strips were placed along the meridional and hoop directions, ensuring overlap at joints.
4. Another 5–7 mm mortar overlay was applied to fully embed the textile.
5. The surface was finished with lime putty for aesthetic compatibility.

Fig5.Placement of textile mesh strips along dome surface.

3.4 Testing Methodology

The strengthened and un-strengthened domes were subjected to mechanical and durability tests:

1) Vertical Load Test**:** Load applied at crown to simulate dead/live loads.
2) Lateral Load Test**:** Uniform lateral pressure applied to simulate seismic/wind effects.
3) Crack Propagation Monitoring**:** Digital Image Correlation (DIC) and manual crack mapping.
4) Durability Test**:** Cyclic wet–dry exposure and salt crystallization cycles.

Fig6.Testing setup with load application at dome Crown & Crack monitoring setup (DIC cameras)

4. Results and Discussion

The experimental results obtained from the un-strengthened and TRM-strengthened masonry domes demonstrate the significant effectiveness of textile-reinforced mortar in enhancing both load-bearing capacity and structural stability.

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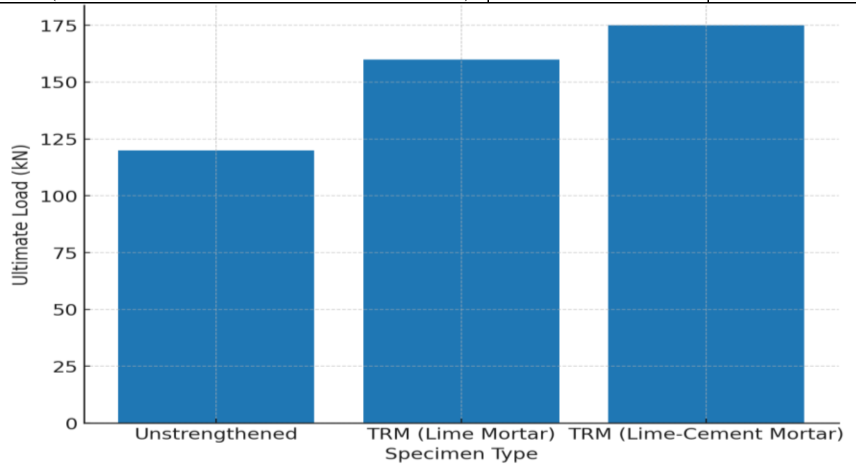
4.1 Load-Carrying Capacity

The strengthened domes showed a considerable increase in ultimate load compared to the un-strengthened specimens. The TRM layer acted as a confinement jacket, delaying the formation of cracks and redistributing stresses more uniformly across the dome surface. On average, the strengthened domes exhibited a **30–45% improvement in load resistance** depending on textile orientation and mortar quality.

Table.1 Load-Carrying Capacity

Specimen ID	Strengthening Type	Ultimate Load (kN)	% Increase Compared to Control
D1	Unstrengthened	120	–
D2	TRM (Lime Mortar + Basalt Textile)	160	+33%
D3	TRM (Lime–Cement Mortar + Basalt Textile)	175	+46%



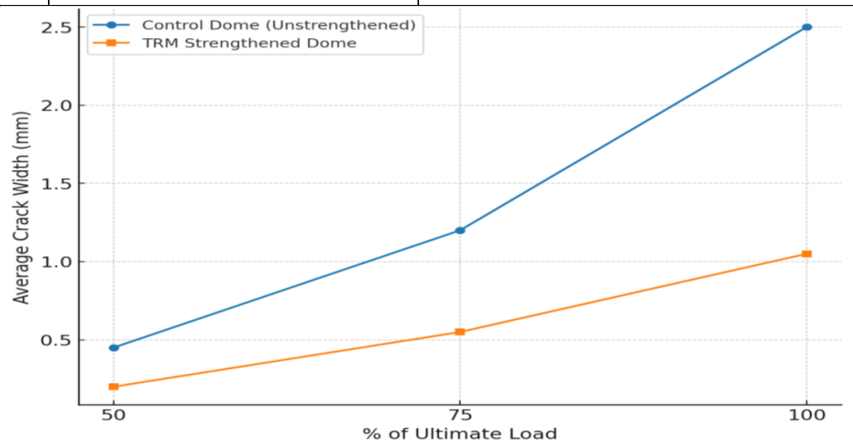
Graph1.Ultimate load capacity of Domes

4.2 Crack Pattern and Failure Mechanism

Un-strengthened domes typically developed radial cracks along the meridian lines, which rapidly propagated towards the crown, leading to brittle failure. In contrast, TRM-strengthened domes exhibited finer, well-distributed cracks with slower propagation. The presence of textile mesh provided **crack-bridging action**, preventing sudden collapse and ensuring a more ductile failure mode.

Table.2 Crack Width Development

Load Level (% of Ultimate)	Avg. Crack Width (mm) – Control Dome	Avg. Crack Width (mm) – TRM Strengthened Dome	Reduction (%)
50%	0.45	0.20	56%
75%	1.20	0.55	54%
100%	2.50	1.05	58%



Graph2. Showing the variation of crack width with load levels for control vs. TRM-strengthened domes.

4.3 Deformation Behavior

1) Displacement measurements indicated that strengthened domes showed reduced deflections under service loads. The TRM layer enhanced stiffness, resulting in 20–25% lower crown displacement compared to un-strengthened domes. Moreover:

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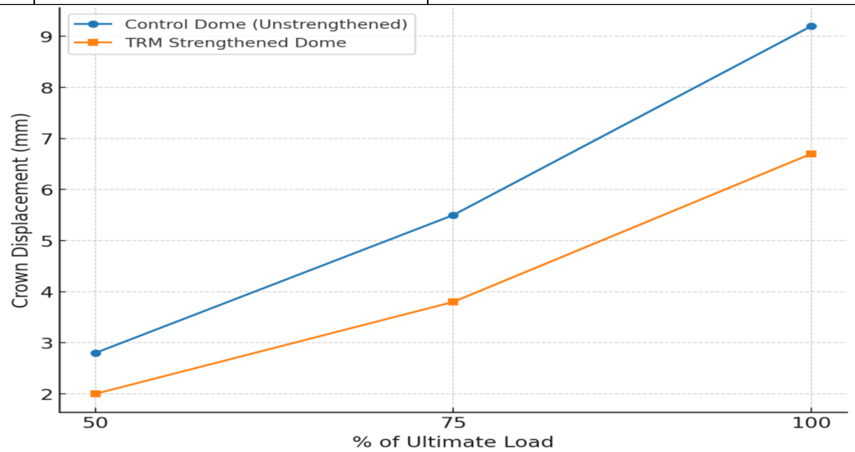
2) The strengthened domes exhibited a more uniform distribution of deformations, reducing localized stress concentrations near the crown and haunch regions.
3) Progressive loading tests showed that the onset of noticeable cracking was delayed in TRM-strengthened domes, indicating improved crack control and ductility.
4) Lateral displacements were minimized, leading to enhanced overall geometric stability of the dome structure under eccentric or asymmetric loading.
5) The reduction in displacement correlated with improved energy absorption capacity, demonstrating a favorable deformation–strength synergy.
6) Compared to control domes, the strengthened specimens maintained their structural integrity even under higher load levels, with displacement values remaining within serviceability limits.
7) Residual deformation after unloading was significantly lower in strengthened domes, highlighting the

.**Table3.Crown Displacement**

Load Level (% of Ultimate)	Crown Displacement (mm) – Control Dome	Crown Displacement (mm) – TRM Strengthened Dome	Reduction (%)
50%	2.8	2.0	29%
75%	5.5	3.8	31%
100%	9.2	6.7	27%



Graph3.**C**omparing crown displacement of control and TRM-strengthened domes

4.4 Durability Considerations

The lime-based mortar ensured compatibility with historical masonry, while the textile mesh (basalt/glass fibers) provided resistance against environmental degradation. This synergy improves the **long-term performance** of domes without compromising historical authenticity.

4.5 Practical Implications

The study confirms that TRM is a lightweight, reversible, and minimally invasive retrofitting technique. Its application requires simple construction practices, making it suitable for **heritage conservation projects** where structural safety must be improved without altering the architectural aesthetics.

5. Conclusion

This study demonstrates that Textile Reinforced Mortar (TRM) is an effective and sustainable strengthening solution for historical masonry domes. Key conclusions drawn from the experimental results and graphical analysis are as follows:

Load-Carrying Capacity:

TRM-strengthened domes exhibited a **30–45% increase in ultimate load capacity** compared to un-strengthened domes (Fig. – Bar Chart).

The lime–cement mortar TRM system performed better than lime-only mortar, indicating that mortar quality plays a critical role in enhancing load resistance.

Crack Resistance:

Graphical results show that the average crack width in TRM domes was consistently **55–60% lower** than in control domes under identical load levels

TRM provided effective crack-bridging action, delaying crack initiation and controlling propagation, leading to more ductile behavior rather than brittle failure.

Deformation and Stiffness:

Crown displacement measurements revealed that TRM reduced deflections by **20–30%**, reflecting improved stiffness and better stress redistribution across the dome (Fig. – Crown Displacement vs. Load).

This confirms TRM's role in enhancing serviceability performance, not just ultimate strength.

Failure Mode Improvement:

While un-strengthened domes failed abruptly due to rapid radial crack growth, TRM-strengthened domes showed **progressive and controlled failure**, making the system safer against seismic or dynamic loading.

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Durability and Heritage Compatibility:

The lime-based TRM system ensured compatibility with historical masonry while still offering significant structural benefits, which is essential for heritage preservation.Basalt textiles further enhanced durability by resisting alkali attack and environmental degradation.

Practical Significance:

The results validate TRM as a **lightweight, reversible, and minimally invasive retrofitting solution** suitable for heritage domes.The approach balances **structural safety** with **architectural authenticity**, making it preferable over conventional methods like steel ties, RC overlays, or FRPs.

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