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Diagonal Compression Tests on Masonry Walls Strengthened with Natural TRM: Scale Effects and Retrofitting Efficiency

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Abstract

This contribution presents the results of a comprehensive experimental campaign consisting of 36 diagonal compression tests on unreinforced and reinforced masonry walls. Two geometries were examined—120×120 cm and 60×60 cm—to assess the influence of scale on shear response and failure mechanisms. Strengthening systems included jute diaton and a bidirectional Flax Fiber net embedded in a lime-based mortar, developed within the IntegraTRM PRIN project. Test results highlight the effectiveness of both reinforcement configurations in enhancing shear strength and deformation capacity, while offering insights into scale-dependent behaviour and the mechanical efficiency of natural-fiber TRM strengthening. The work contributes to the development of sustainable seismic-retrofitting systems based on bio-based components, providing experimental evidence useful for future analytical modelling and for establishing performance-oriented design criteria tailored to natural-fiber composites. Moreover, the results allow a deeper understanding of the interaction between the flax-based textiles and the masonry substrate, clarifying failure modes, crack patterns, and load-transfer mechanisms. These findings support the feasibility of natural-fiber TRM as a low-carbon, cost-effective alternative for strengthening existing masonry structures.

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1. Introduction

Sustainable retrofitting of existing masonry structures has emerged as a central objective in structural engineering, balancing enhanced performance with material compatibility, reversibility, and minimal architectural impact (Cassese et al. 2022; Ungureanu et al. 2021; Pepe et al. 2023) .

Among retrofit strategies, textile-reinforced mortars (TRM) and related inorganic-matrix composites have attracted considerable attention as durable, fire-resistant, and vapor-permeable alternatives to traditional FRP systems when working with historic or porous masonry substrates (Ungureanu et al. 2021; Pepe et al. 2023; Dalalbashi et al. 2022). TRM/NTRM systems embed textile fabrics in lime- or other hydraulic lime-based matrices and are externally bonded to masonry to improve in-plane shear resistance, post-cracking behavior, and overall ductility, while maintaining compatibility with historic substrates and reversible intervention options where feasible.

Natural fibers (e.g., flax, jute, hemp) within TRM/NTRM systems offer additional environmental and sustainability advantages due to renewability and reduced embodied energy, with growing experimental evidence supporting their effectiveness for strengthening historic masonry under in-plane and out-of-plane loading (Majumder et al. 2025, 2024, 2022; Corradi et al. 2021; Ferrara et al. 2021).

However, durability challenges—particularly moisture sensitivity and matrix alkalinity interactions with natural fibers—remain active areas of research, necessitating careful selection of matrices, fiber pretreatment, and interface engineering to ensure long-term performance (Agossou et al. 2025; Abbass et al. 2020; Pepe et al. 2023; Illampas et al. 2023; Sadrolodabae et al. 2021). Diagonal compression tests and related in-plane shear configurations have become standard experimental approaches to quantify shear strength, stiffness, deformation capacity, and failure mechanisms in TRM-strengthened panels, enabling direct comparisons across substrates and retrofit systems (Ungureanu et al. 2021; Pepe et al. 2023; Ferrara et al. 2021; Illampas et al. 2023; Trochoutsou et al. 2022).

Moreover, although diagonal compression tests are widely adopted to characterize the in-plane shear behavior of strengthened masonry panels, existing studies mainly focus on strength enhancement, while a comprehensive understanding of failure mechanisms, crack evolution, and scale effects remains limited. In particular, the role of natural-fiber TRM systems in controlling crack distribution and modifying the collapse mechanism has not yet been fully clarified, especially when different panel sizes are considered.

Within this context, the present study addresses the experimental gap concerning the in-plane shear performance and failure mechanisms of masonry walls strengthened with natural-fiber textile-reinforced lime mortars, with particular emphasis on scale-dependent behavior.

The experimental campaign includes 36 diagonal compression tests on masonry panels of two different sizes (120×120 cm and 60×60 cm), strengthened using flax/jute-based TRM systems and diaton connectors. The investigation focuses on key mechanical parameters such as shear capacity, deformation response, crack patterns, and failure modes, with the aim of evaluating the effectiveness of sustainable reinforcement solutions and their interaction with the masonry substrate.

The results provide new insights into the influence of scale and reinforcement configuration on structural response, contributing to the development of performance-based design approaches for natural-fiber TRM systems and supporting their application in sustainable and compatible retrofitting of existing masonry structures.

Nomenclature

TRM	textile-reinforced mortars
NTRM	natural textile-reinforced mortars

2. Materials and Methods

2.1. Materials

The experimental campaign was designed to investigate a sustainable textile-reinforced mortar (TRM) system based on natural and recycled materials for masonry retrofitting.

The masonry walls were constructed using solid clay bricks ($250 \times 120 \times 50$ mm) bonded with lime-based mortar. The binder consisted of natural hydraulic lime (NHL 5), selected for its chemical and mechanical compatibility with historic substrates, low soluble salt content, and stable hydraulic reaction products. The mortar was prepared by mixing NHL with aggregates and water, using a dosage of approximately $350\text{--}400$ kg/m³ of binder, ensuring adequate workability and mechanical performance. A composite mortar was developed by combining: natural sand (70%) and recycled sand (30%) from construction and demolition waste, natural hydraulic lime (NHL 5) as binder, chopped sheep wool fibers, incorporated to enhance thermal insulation properties and crack control.

For structural strengthening, a flax fiber textile mesh (NFL-NET 300 BA) was employed. This bidirectional natural fiber grid is characterized by: mesh size: 10×10 mm, areal weight: ≈ 310 g/m², tensile strength: ≈ 216 MPa,

elastic modulus: ≈ 5.3 GPa, ultimate strain: $\approx 4.3\%$. The flax textile was selected due to its low environmental impact, renewability, and good mechanical performance, offering a sustainable alternative to conventional synthetic fibers.

In selected configurations, jute fiber diatons were introduced as transverse connectors to improve the through-thickness mechanical response and integrity of the masonry panels. See Figure 1 for materials overview. The jute diatons were handcrafted using Bangla Tosha (*Corchorus olitorius*) jute fibers and employed as through-thickness connectors to improve the bond between the masonry substrate and the external strengthening layers. Following the procedure described in Majumder et al. (2022), each diaton was fabricated using approximately 25 g of jute fibers, with bundles of approximately 65 cm long fibers twisted together to form the core and additional fibers wrapped around to ensure integrity and mechanical stability. The average diameter of the diatons was approximately 15.5 mm (CoV = 9.68%). In the strengthened specimens, the diatons were arranged to maintain a consistent density of approximately 2.78 diatons/m². Specifically, four diatons were adopted for the 120×120 cm wall panels (distributed in a regular 2×2 arrangement), whereas one centrally positioned diaton was used for the 60×60 cm specimens.



Fig. 1: Materials used for the wall preparation. The strengthening configuration included jute diatons with a constant density of approximately 2.78 diatons/m²

2.2. Specimen Design and Configurations

Two specimen sizes were considered: 120×120 cm panels, used for diagonal compression tests according to ASTM E519 (C15 Committee, n.d.), 60×60 cm panels, used for both thermal characterization and subsequent mechanical testing to evaluate scale effects. The reference (unreinforced) masonry walls had a thickness of 120 mm, while retrofitted specimens reached a total thickness of approximately 180 mm due to the addition of strengthening and/or insulating layers.

Several retrofitting configurations were investigated in order to evaluate the influence of the strengthening technique on the mechanical behaviour of the panels. Three panels were tested for each configuration reported in Table 1.

Table 1. Tested configurations.

Configuration	Description
NR	Unreinforced masonry
TL	Masonry with external mortar layer
TRM	Flax textile reinforced mortar
TRMTL	TRM combined with thermal layer
TRMD	TRM with diaton connectors
TRMTLD	TRM with thermal layer and diaton

2.3. Strengthening Procedure

The TRM strengthening system was applied using an inorganic matrix, following standard procedures for lime-based composites. The application consisted of: surface preparation and substrate saturation, application of a first layer of fresh mortar, placement of the flax textile mesh embedded within the mortar, ensuring a minimum overlap of 100 mm, application of a second mortar layer before initial setting of the first layer.

The thickness of the TRM layer was approximately 30 mm per side, ensuring effective stress transfer between textile and substrate. For configurations including diatons, jute fiber connectors were inserted across the thickness prior to the application of the external layers, enhancing out-of-plane stability and internal load redistribution. For configurations including diatons, jute fiber connectors were inserted across the wall thickness prior to the application of the external layers, according to the arrangement reported in Section 2.1. The diatons acted as transverse connectors enhancing interlayer mechanical interaction, reducing potential delamination phenomena, and improving internal load redistribution.

2.4. Experimental Setup and Mechanical Testing

The mechanical behavior of the masonry panels was assessed through diagonal compression tests in accordance with ASTM E519 (C15 Committee, n.d.), which provides a reliable evaluation of in-plane shear response.

The test setup, see Figure 2, consisted of: a rigid steel loading frame, a hydraulic actuator (capacity ≈ 500 kN), steel loading shoes to ensure uniform stress distribution, load measurement via strain-gauge load cell, displacement measurement using LVDTs positioned along the diagonals.

This configuration allows capturing the interaction between masonry substrate, mortar matrix, and textile reinforcement, including debonding and crack propagation mechanisms.

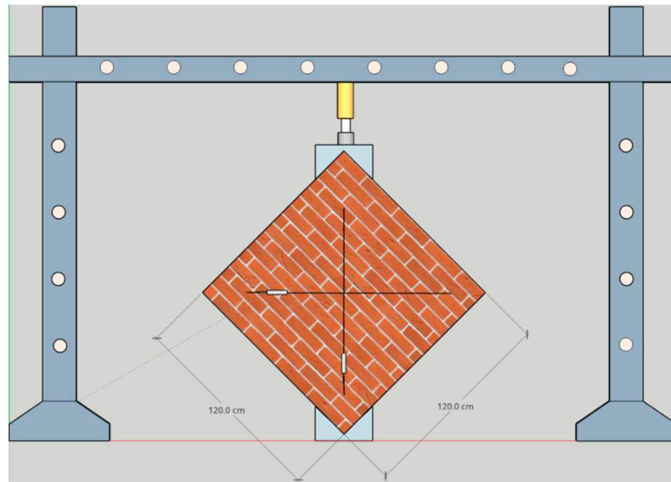


Fig. 2: Experimental Set-up.

3. Results

The average collapse loads obtained from the tests on both the 120 cm and 60 cm panels are summarized in Table 2. For each configurations three panels have been tested.

The results highlight a clear influence of the retrofitting strategy on the in-plane shear capacity of masonry panels. For the 120×120 cm specimens, the reference unreinforced configuration (NR) exhibited an average collapse load of 85.65 kN, representing the baseline structural capacity. The application of a thermal layer only (TL) led to a significant increase in load capacity (+91%), reaching 163.87 kN, indicating that even non-structural layers contribute to confinement and stress redistribution.

The TRM-strengthened configuration achieved the highest performance, with a collapse load of 257.38 kN, corresponding to an increase of approximately +200% compared to NR. This confirms the effectiveness of flax-based TRM systems in enhancing shear resistance and crack control.

The combined TRM-TL system showed a lower capacity (161.29 kN) compared to TRM alone, suggesting that the presence of the thermal layer may reduce the efficiency of stress transfer between the textile and the substrate.

The introduction of diatons (TRMD) resulted in a moderate increase (176.30 kN) compared to TL and TRMTL configurations, although still lower than TRM alone. The fully integrated system (TRMTLD) reached 182.68 kN, indicating a balanced but not optimal structural response.

For the 60×60 cm specimens, the NR configuration showed a higher collapse load (113.73 kN) due to scale effects and reduced slenderness. The TL configuration again improved the capacity (178.18 kN, +57%).

In contrast to the larger specimens, the TRM configuration (149.72 kN) did not provide the highest strength increase, while the TRMD configuration exhibited the best performance (189.40 kN). The combined TRMTLD system showed intermediate behavior (152.82 kN).

Table 2. Results.

Configuration	Collapse Load (kN) 120x120 cm	Collapse Load (kN) 60x60 cm
NR	85.65	113.73
TL	163.87	178.18
TRM	257.38	149.72
TRMTL	161.29	132.22
TRMD	176.30	189.40
TRMTLD	182.68	152.82

4. Discussion

The results demonstrate that the flax-based TRM system is highly effective in enhancing the in-plane shear capacity, particularly for larger-scale masonry panels. The significant increase observed in the 120×120 cm specimens confirms the ability of the textile reinforcement to bridge cracks, delay crack propagation, and improve stress redistribution within the panel. However, the results also reveal that system interaction effects are non-trivial. The presence of the thermal layer alone contributes to strength enhancement due to increased thickness, improved confinement, and partial stress redistribution. Nevertheless, when combined with TRM (TRMTL), a reduction in structural efficiency is observed, suggesting that the insulating mortar may reduce bond effectiveness, introduce a more deformable interface, and limit the activation of the textile reinforcement.

The inclusion of diatons improves the through-thickness mechanical behavior, particularly evident in the smaller specimens where TRMD provides the highest capacity. This indicates that: diatons enhance load transfer between layers, they reduce delamination phenomena, they are more effective when the panel thickness-to-size ratio is lower. However, in larger panels, the presence of diatons does not surpass the performance of TRM alone, suggesting that in-plane reinforcement governs the response at that scale.

A clear scale dependency is observed: larger panels benefit more from TRM reinforcement, smaller panels show enhanced sensitivity to transverse reinforcement (diatons). This highlights the importance of considering geometric effects and boundary conditions when designing retrofit interventions.

The observed failure modes indicate: brittle diagonal cracking for NR and TL specimens, distributed cracking and improved ductility for TRM systems and localized debonding or interface sliding in combined systems (TRMTL, TRMTLD).

Figure 3 provides a clear comparison between the collapse mechanisms of the 120TL specimen (left) and the 120TRMD specimen (right), highlighting the fundamental role of textile reinforcement in governing failure evolution.

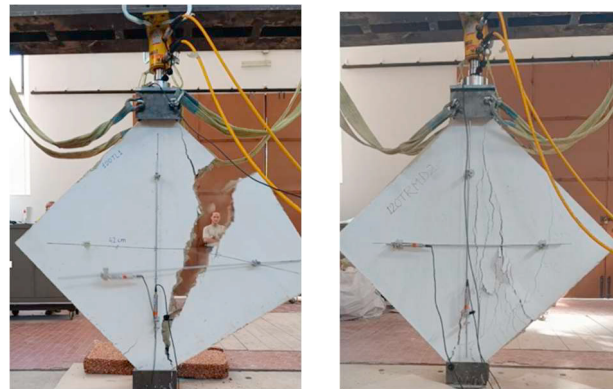


Fig. 3: Collapse mechanism for 120TL specimen (left) and 120TRMD (right).

In the 120TL configuration, the collapse is characterized by a single dominant diagonal crack, extending rapidly from one corner to the opposite one. The crack is wide, well-localized, and develops abruptly, indicating a brittle shear failure mechanism. The absence of reinforcement leads to: limited stress redistribution capacity and rapid loss of load-carrying capacity after crack initiation with negligible post-peak resistance. This behavior is typical of unreinforced or weakly confined masonry, where failure is governed by the tensile weakness of mortar joints and brick–mortar interfaces, resulting in a sudden and unstable collapse.

Conversely, the 120TRMD specimen exhibits a markedly different behavior. The presence of the flax textile mesh and diatons promotes a distributed cracking pattern, with multiple finer cracks developing along the diagonal rather

than a single macro-crack. The textile reinforcement bridges cracks limiting their opening and enables stress transfer across cracked sections. As a result, the failure mechanism becomes progressive rather than abrupt, with a clear increase in energy dissipation capacity. The crack pattern is more diffuse and controlled, indicating a pseudo-ductile response. Additionally, the presence of diatons contributes to maintaining the integrity through the thickness, reducing out-of-plane separation and limiting delamination between layers. This effect is particularly evident in the more uniform crack distribution observed in the reinforced specimen.

The comparison highlights two fundamentally different structural behaviors, with unreinforced and TL systems exhibiting brittle and localized failure, while TRM-based systems promote distributed cracking and a more controlled damage evolution. The flax textile plays a key role in transforming the failure mode by activating tensile resistance after cracking, increasing the effectiveness of shear transfer mechanisms, and promoting a multi-crack regime rather than the formation of a single dominant fracture plane. This transition from localized to distributed cracking is particularly relevant in seismic applications, as it enhances ductility, improves residual load-carrying capacity, and significantly reduces the likelihood of sudden collapse. These observations indicate that the effectiveness of TRM systems should not be assessed solely in terms of peak strength, but must also account for their ability to control crack propagation, ensure a more uniform damage distribution, and fundamentally modify the failure mechanism toward a more stable and predictable structural response.

In this context, flax-based TRM systems demonstrate the ability to significantly improve the structural robustness of masonry, even when combined with additional layers, by ensuring a more stable and predictable collapse mechanism.

5. Conclusions

This study provides an experimental assessment of sustainable flax-based TRM systems for masonry strengthening under diagonal compression, contributing to the growing body of research on compatible and low-impact retrofit solutions for existing structures. The results confirm that TRM strengthening is the most effective solution, providing up to a 200% increase in collapse load for large-scale panels, in agreement with previous findings on inorganic-matrix composites, which highlight their effectiveness in enhancing shear capacity and crack control in masonry elements (Koutas et al. 2019). Thermal layers alone also contribute to mechanical capacity due to increased thickness and confinement; however, their combination with TRM may reduce structural efficiency because of interface compliance and reduced bond effectiveness, a phenomenon consistent with observations reported in layered retrofit systems (Gomes et al. 2019).

The inclusion of diatons improves the through-thickness mechanical response, with particularly significant benefits observed in smaller specimens, confirming their role in enhancing interlayer interaction and limiting delamination, as also discussed in recent studies on FRCM/TRM anchorage systems (Al-Lami et al. 2020). Moreover, the structural response is strongly influenced by scale effects, with different reinforcement mechanisms governing small and large panels, highlighting the importance of considering specimen geometry and boundary conditions in experimental and design phases.

A key outcome of this work is the identification of the fundamental role played by the interaction between textile, mortar matrix, and substrate, which governs stress transfer, crack distribution, and overall failure mode. This aspect is particularly critical in multi-layer systems, where interface behavior can significantly alter the effectiveness of the strengthening intervention (Raoof et al. 2016).

Finally, flax-based TRM systems emerge as a promising low-carbon alternative to conventional strengthening techniques, combining mechanical effectiveness with material compatibility and sustainability. Their use aligns with current research trends promoting natural fiber composites for structural applications, which demonstrate reduced environmental impact while maintaining adequate mechanical performance. These findings support the adoption of bio-based TRM systems in the retrofit of existing masonry buildings, particularly in heritage contexts where compatibility and reversibility are key requirements.

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