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Strengthening of Masonry Walls Using Jute Fiber: Merging Structural and Thermal Upgrading/Retrofitting

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Abstract

In the past five decades, man-made and synthetic fibers have dominated the market and have been used to strengthen masonry structures. This study explores the feasibility of using natural fibers, specifically jute fiber-based materials, to improve masonry walls' structural and thermal performance through integrated upgrading/retrofitting. It thoroughly examines the application of jute nets (with mesh dimensions of 2.5 cm × 1.25 cm), jute fiber diatoms, and jute fiber-reinforced composite mortar (containing 1% jute fiber by dry mortar weight) in masonry strengthening. The research assesses the impact of these materials on both the structural integrity and thermal efficiency of upgraded masonry walls. Remarkably, the use of Natural Fiber Textile Reinforced Mortar (NFTRM) led to an increase of more than 500% in the walls' load-bearing capacity and improved insulation by 36%. Additionally, the study incorporates detailed crack pattern analysis under in-plane cyclic loading using advanced DIC techniques. Therefore, integrated upgrading/retrofitting has been demonstrated to be an ideal solution against seismic action while enhancing the energy efficiency of a building.

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1. Introduction

The construction and building (C&B) sector is a leading contributor to global carbon emissions, responsible for approximately 39% of global greenhouse gas (GHG) emissions and 36% of total energy consumption, whereas in the European Union, the sector accounts for 36% of GHG emissions and 40% of energy use [1] [2]. These numbers underscore the urgent need for sustainable practices in the construction and building sector, particularly in retrofitting and upgrading existing masonry structures to enhance both structural integrity and energy efficiency.

Fiber-Reinforced Polymer (FRP) [3] systems have been widely used for structural strengthening due to their high strength and established design standards. Whereas, the Textile Reinforced Mortar (TRM) systems are also gaining momentum, and it offers several advantages: improved fire resistance, better compatibility with masonry substrates, high mechanical performance, and environmental resilience [4]. TRM systems avoid the use of organic resins and perform reliably even under high temperatures, making them suitable for masonry retrofitting in diverse climates. Currently, the majority of TRM applications rely on synthetic fibers such as carbon, glass, basalt etc. Notably, these materials offer excellent strength and durability; however, they are very energy-intensive, resulting in a higher carbon footprint. In response, research into natural fiber alternatives has accelerated. Natural fibers like jute, hemp, sisal, flax, and banana fiber are being explored due to their renewability, lower embodied energy, and environmental benefits [4]. Some notable integrated (structural and thermal) retrofitting research works can be found in [5] [6] [7] [8] [9] [10]. However, the majority of these studies have focused on structural performance, while the improvement in thermal properties has been considered due to the application of Expandable Polystyrene (EPS) in the retrofitting system. Moreover, the studies on natural fiber TRM (NFTRM) have primarily focused on structural retrofitting [4].

The study presented here introduces a novel, fully jute fiber-based NFTRM system that integrates structural strengthening with thermal enhancement. The system includes jute fiber nets, jute diatoms, and a jute-based composite mortar, used together for the first time in a single TRM configuration. The research investigates the structural and thermal performance of this integrated system through in-plane cyclic tests and thermal conductance measurements. Furthermore, the crack patterns were analyzed using digital image correlation (DIC) techniques.

This paper is organized as follows: after a brief Introduction (Section 1), Section 2 highlights the materials and methods used; Section 3 presents the results and observations; Section 4 concludes with key findings.

2. Material and methods

Fig 1 presents the schematic representation of the masonry wall integrated (Structural and thermal) retrofitting/upgrading scheme.

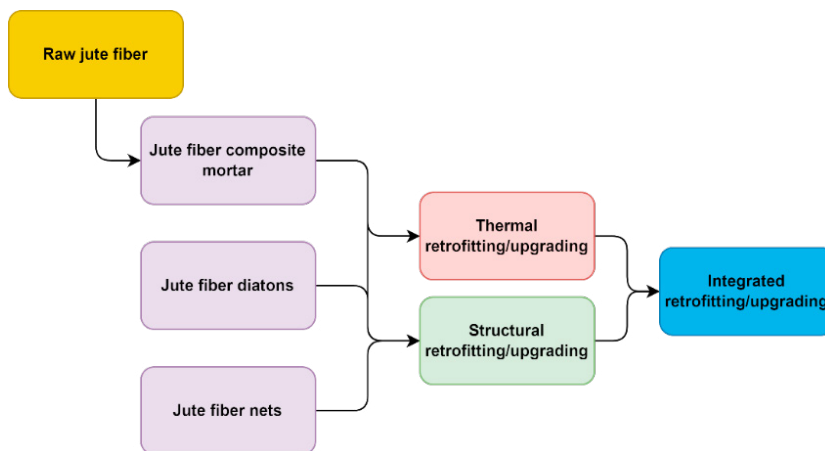


Fig 1. Schematic diagram of the flow of work for integrated retrofitting.

2.1. Materials

2.1.1. Jute fiber made products

For this experimental campaign, the jute fiber and jute fiber threads (Bangla Tosha – Corchorus olitorius) were sourced from West Bengal, India. These raw jute fibers (Fig 2.a) were subsequently used to fabricate jute fiber diatons (Fig 2.b), which played a crucial role in the structural strengthening of the masonry walls. The diatons serve as key structural elements primarily aimed at enhancing shear resistance in the structures to which they are applied. The same raw jute fibers were also chopped into 30 mm fiber lengths for use in preparing the composite mortar, primarily for thermal retrofitting. Jute nets (Fig 2.c) of 1 m × 1 m dimension (wall specimens used for structural test) and 0.9 m × 0.7 m (wall specimens used for thermal test), were prepared manually, and are used on both faces of the masonry wall for structural strengthening. The mechanical properties of the raw jute fiber, jute fiber nets, and jute fiber diatons are provided in Table 1 (For more details, see [50]).

Fig 2.d represents the masonry wall upgrading process with jute fiber products (diatons, nets, and composite mortar).

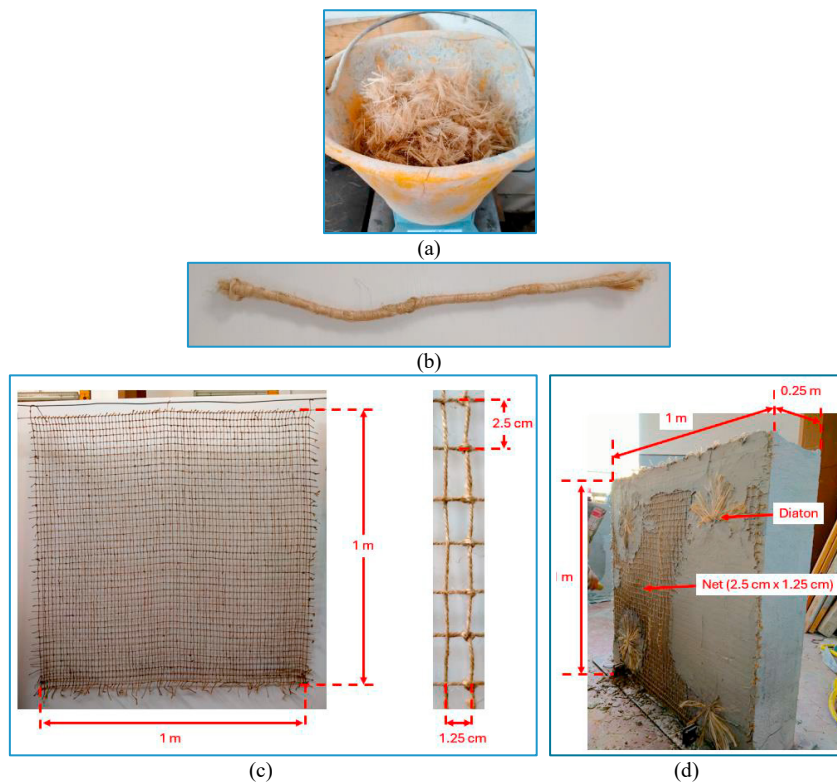


Fig 2. (a) Raw jute fiber, (b) Jute diaton, (c) Jute net, and (d) retrofitted masonry wall.

Table 1. The mechanical properties of the raw jute fiber, jute fiber diatons, and jute fiber nets [11] [12].

Category	Product	Tensile Strength [MPa]	Strain Energy [kJ·mm]	Max Axial Strain / Displacement	Stiffness [N/mm]	Max Load [N]	Coefficient of Variation (Co.V.)
Raw Material	Raw fiber	215.1	0.8	0.013 (strain)	—	—	4.4%, 58.9%, 19.1%
Structural Unit	Diatons	15.5	14.18	0.03 (strain)	—	—	20.8%, 53.9%, 23.6%
Structural Unit	Jute net (2.5×1.25 cm mesh)	—	8.8	72.5 mm (displacement)	7.6	217.3	20.2%, 39.1%, 17.8%, 24.8%

2.1.2. Mortar used

The mortar used is a pre-mixed masonry mortar made from hydraulic binders and selected aggregates, compliant with UNI EN 998-2 [13]. It has a dry density of 1545 kg/m³, compressive strength of M10 (10 N/mm²), and thermal conductivity of 0.83 W/mK. A jute-fiber composite mortar was created by adding 1% of (30 mm fiber lengths) jute fiber with around 22% water (relative to total mass).

2.2. Methods

The thermo-structural performance of the masonry walls (un-strengthened and retrofitted/upgraded) was studied in two separate steps. The structural behavior was analyzed using in-plane cyclic tests, whereas the thermal performance of the masonry walls was evaluated using a dedicated Climate Chamber (CC) through thermal conductance tests.

2.2.1. Structural performance

To assess the structural performance of masonry walls, both un-strengthened and retrofitted/upgraded specimens were tested under a fixed 4-ton vertical load using hydraulic jack H1, simulating the structural weight. In-plane cyclic lateral loads were applied alternately by jacks H2 and H3 until failure. Fig 3 shows the setup, including three displacement transducers T(G) and T(F) placed diagonally, while T(M) has been placed horizontally to measure wall deformations. These transducers, with a maximum capacity of 100 mm and a resolution of one μm , captured precise displacement data. The lateral loads increased across three cycles (a combination of applied loads by H2 and H3 was considered a complete cycle), applied alternately from both sides. This setup was selected to effectively simulate and mimic earthquake conditions, allowing for a comparison of the performance between the un-strengthened and NFTRM retrofitted/upgraded walls.

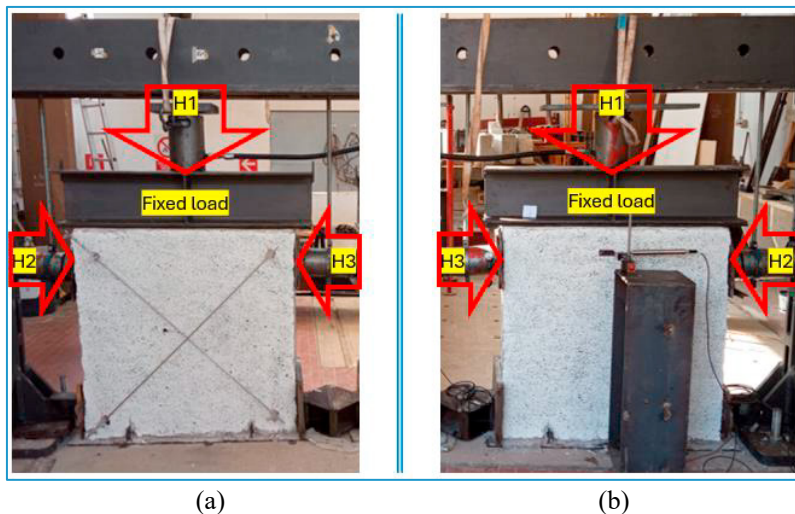


Fig 3. In-plane cyclic test setup with hydraulic jacks used: (a) front view with and (b) back view.

2.2.2. Thermal performance

The Biemme TH Climate Chamber (CC), shown in Fig 4.a, was used to evaluate the thermal performance of the un-strengthened and NFTRM retrofitted/upgraded masonry walls. It consists of two movable chambers and a fixed central wall, and it has been built according to EN 1934:2000 [14]. Masonry wall samples (0.9 m × 0.7 m × 0.25 m) were placed within an EPS enclosure (Fig 4.b) that acts as a heat barrier. Heat flux meters ($\pm 5\%$ accuracy at 20°C) and Class A platinum temperature sensors were used for thermal flux and temperature measurements, respectively.

Notably, the cold chamber was set to have 2°C, 50% RH, and 10.1 m/s ventilation, while the hot chamber was maintained at 20°C, 50% RH, and 1.1 m/s ventilation. Notably, the measurements have been performed step by step: the first test was conducted with the un-strengthened masonry wall (Fig 4.c), then layer of TRM (consisting of mortar, net and diatons) has been added on both sides of the masonry wall and the second test was performed, and subsequently the final test has been done after the addition of the thermal layers (jute fiber composite mortar) on both faces. Fig 4.d represents the schematic diagram of the complete retrofitted/upgraded wall sample with different thermal resistances, considered for the thermal transmittance calculation.

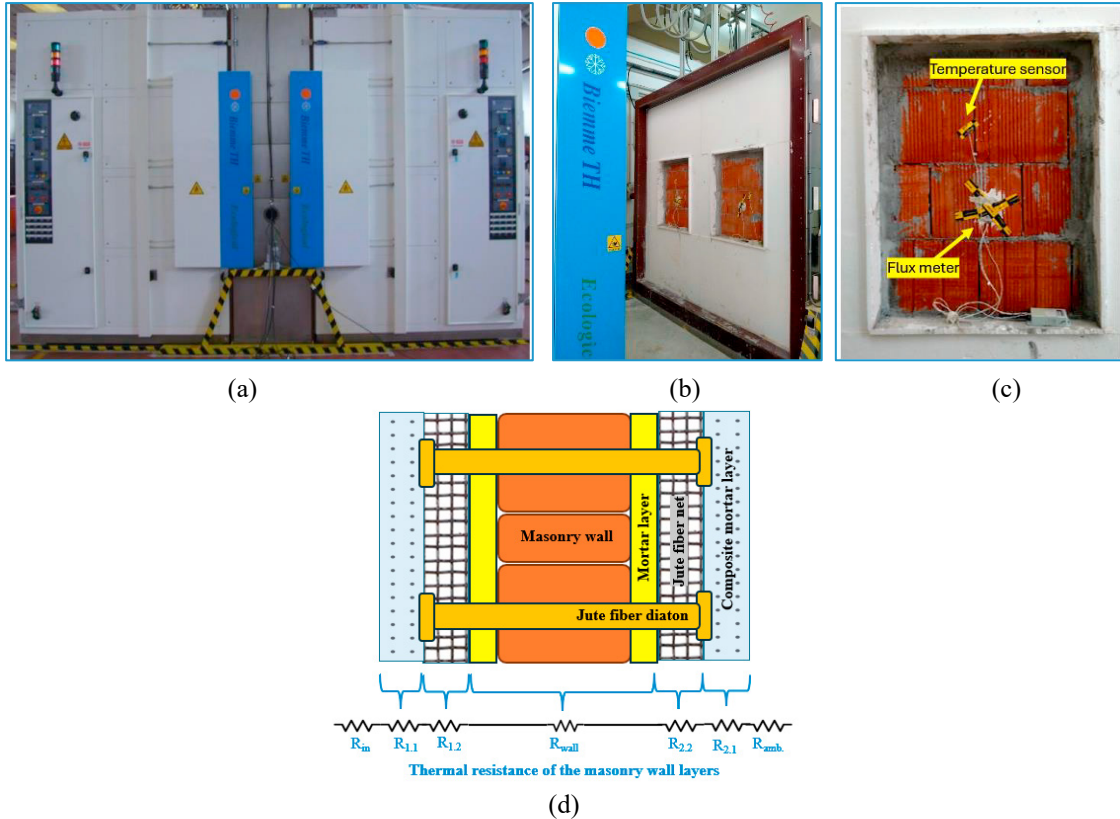


Fig 4. (a) Climate chamber, (b) central wall with specimens, (c) masonry wall and (b) schematic diagram of wall sample showing thermal resistances.

2.2.3. Digital image correction (DIC)

All un-strengthened and NFTRM retrofitted/upgraded masonry wall specimens were prepared for the Digital Image Correlation (DIC) analysis following the procedures mentioned in [15].

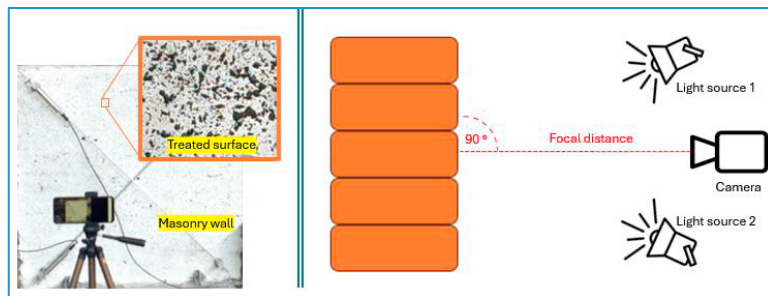


Fig 5. DIC test set up.

First, the surfaces of the wall specimens were painted white and randomly sprayed with black speckles to create a suitable pattern for image tracking, as shown in Fig 5. The GOM software was used to perform DIC analysis. The camera setup was carefully calibrated, with a resolution of 1920×1080 pixels and a focal distance of approximately 237 cm. The camera was positioned directly in front of the specimen, and two high-intensity light sources provided uniform illumination. Images were captured at 0.5-second intervals in synchronization with the load-displacement system. GOM Correlate software processed 115 selected images. This analysis enabled precise measurement of crack openings at peak displacement.

3. Results

3.1. Integrated retrofitting/upgrading

Strength improvement: Fig 5 presents the load-displacement comparison curves between the un-retrofitted and the NFTRM retrofitted masonry walls.

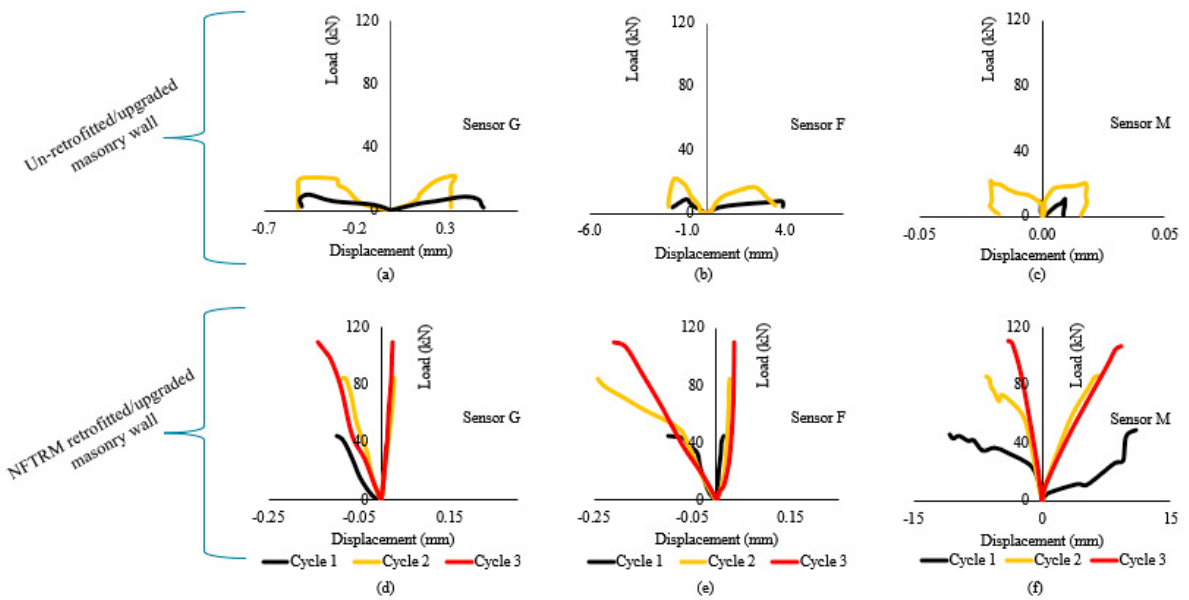


Fig 6. Load-displacement graphs: (a)

The positively improved results clearly demonstrate the effectiveness of the jute fiber-based products (jute fiber nets and diatoms, and jute fiber composite mortar) used for NFTRM retrofitting technique in enhancing structural performance under cyclic loading. In the un-retrofitted masonry wall (top row: subfigures a-c), the load-displacement curves exhibit minimal load-bearing capacity. In contrast, the NFTRM-retrofitted wall (bottom row, subfigures d-f) exhibits significantly improved performance, with peak loads in the third cycle reaching approximately 120 kN.

Ultimately, both masonry (un-retrofitted/upgraded and NFTRM retrofitted/upgraded) walls were subjected to the ultimate load cycle (maximum load-bearing capacity), and the load was applied until the walls collapsed.

Notably, it has been observed that the load-bearing capacity of the NFTRM retrofitted/upgraded masonry wall has been increased by more than 500% (see, Table 2). Therefore, these improvements suggest that the NFTRM retrofitting enhances both the strength and ductility of the masonry wall, making it more resilient under repeated loading.

Thermal property improvement: The thermal transmittance value of the masonry wall has been calculated using the equation 1:

$$U = \frac{1}{R_{total}} \text{ (W/m}^2\text{K)} \tag{1}$$

where,

R_{Total} being the total thermal resistance in $\text{m}^2\text{K/W}$.

$$R_{Total} = R_{in.} + R_{1.1} + R_{wall} + R_{2.2} + R_{2.1} + R_{Amb.} \text{ (m}^2\text{K/W)} \tag{2}$$

where, R_{in} = Indoor resistance; $R_{1.1}$ = Composite mortar (towards indoor condition) resistance; $R_{2.1}$ = Net + diatoms + mortar (towards indoor condition) resistance; R_{wall} = Hollow brick resistance; $R_{2.2}$ = Net + diatoms + mortar (towards outdoor condition) resistance; $R_{1.2}$ = Composite mortar (towards outdoor condition) resistance, and R_{amb} = Ambient/outdoor resistance.

Measurements have demonstrated that the thermal transmittance value of the NFTRM retrofitted/upgraded wall decreased significantly when compared with the reference un-strengthened masonry wall (as presented in Table 2).

Table 2. Un-strengthened masonry wall Vs Upgraded/retrofitted masonry wall.

Structural performance (kN)	Thermal performance (W/m ² K)
Load bearing capacity of about 565 %	Thermal transmittance value reduced by 36%.

3.2. DIC analysis

Fig 7 shows the DIC analysis results for an NFTRM-upgraded masonry wall. The pictures used for DIC analysis have been selected from the last ultimate load cycle. The graph in Fig 7 shows the crack propagation over time. Notably, during the ultimate load cycle, the crack opening reaches a maximum up to +7.81 mm. The color mapping highlights various areas with different strains. Even after failure, the wall still showed signs of tensile load transfer due to the presence of jute fiber nets and diatoms, reflecting improved ductility resulting from NFTRM upgrades (which included jute fiber nets, diatoms, and 1% jute fiber-reinforced mortar).

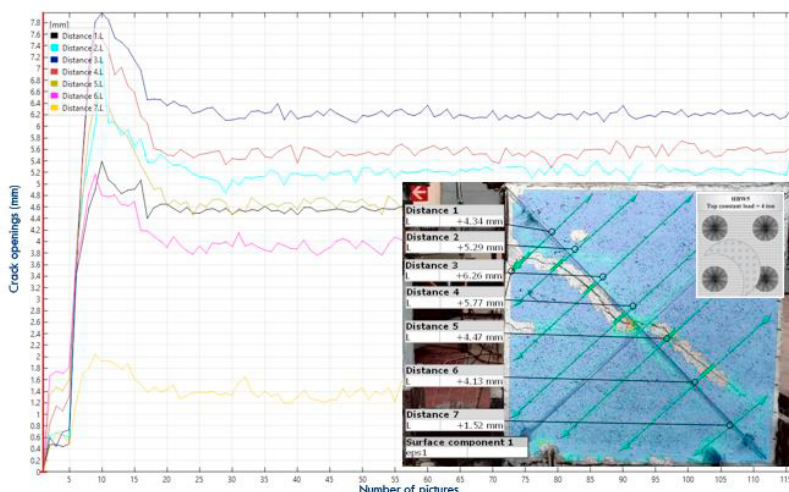


Fig 7. DIC and crack oscillation graph.

4. Conclusion

This study highlights the significant potential of jute fiber-based solutions for improving the structural and thermal performance of masonry walls. By incorporating jute nets, jute fiber diatons, and jute fiber-reinforced composite mortar, the proposed strengthening technique achieved an over 500% increase in load-bearing capacity and a 36% improvement in thermal insulation.

The use of the NFTRM system aligns with sustainable construction practices, providing a cost-effective and eco-friendly alternative to synthetic reinforcement methods.

The results demonstrate clearly that jute fiber can be used as a viable building material to simultaneously enhance the structural integrity and energy efficiency of existing masonry buildings, particularly in contexts that prioritize low environmental impact and increased resilience.

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