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Natural Fiber Textile Reinforced Mortar (NFTRM) for Integrated Masonry Upgrading

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Abstract

The construction and building industry is responsible for a significant amount of carbon emissions due to its high energy consumption throughout the lifecycle of buildings. Many masonry buildings were constructed without following any seismic or energy standards, making them vulnerable to both natural and man-made disasters.

This paper discusses the use of a Natural Fiber (NF) in the Textile Reinforced Mortar (TRM) system, to upgrade or retrofit masonry walls, addressing both structural and thermal issues.

During this campaign, various jute fiber products have been used to upgrade or retrofit the masonry wall to achieve a balanced thermo-structural property for the NFTRM system. Notably, jute fiber nets (with mesh type "2.5 cm x 2.5 cm") and diatons have been used to enhance the strength of the masonry wall. For the thermal upgrading of masonry walls, a combination of 30 mm jute fiber length and 1% jute fiber (based on the dry mortar mass) was chosen for composite mortar preparation.

The use of the jute NFTRM system has resulted in an increased load-bearing capacity (kN) of more than 450% and whereas, an improved insulation capacity, with a reduction of thermal transmittance (W/m^2K) of about 36% have been observed for the upgraded masonry wall, when compared to the un-strengthened masonry wall.

Keywords: *Integrate upgrading, integrated retrofitting, Natural fiber TRM, Jute fiber TRM, Structural and Thermal upgrading/retrofitting.*

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1. Introduction

Today the world is facing various natural, ecological, and environmental disasters. Notably, the majority of the masonry buildings were often constructed without following seismic and energy standards like EN 1998-3 (2005) and EN ISO 52016-1 (2017), respectively, and they are predominantly vulnerable to earthquakes and are often found to be not energy efficient. In a complete life cycle from the construction to the demolition stage, these buildings directly or indirectly consume huge amounts of energy, and this accounts for around 40% in the EU and 36 % globally, as well as they are also accountable for 36 % of CO_2 emissions in the EU and 39% globally as highlighted in Majumder et al., (2024). Therefore, they are directly and indirectly responsible for global warming and its driving effects.

Notably, an integrated upgrading or retrofitting, with a combined structural and thermal approach, can address both aforesaid issues effectively. In a recent study, Triantafillou et al. (2017) have introduced the concept of integrated (structural and energy) retrofitting, which involves making improvements to both the structure and energy efficiency of buildings. The authors in Triantafillou et al. (2017) and Triantafillou et al. (2018) have retrofitted masonry walls with fabric-TRM and glass-TRM systems and evaluated structural improvements through out-of-plane and in-plane tests, respectively. In a separate study, Gkournelos et al. (2020) conducted in-plane and out-of-plane tests to analyze the structural performance of masonry walls, retrofitted using the Glass-TRM system. Similarly, Karlos et al. (2020) have retrofitted masonry walls with a TRM system consisting of glass fabric. They presented detailed experimental, analytical, and numerical model results, which demonstrate the improvement in strength and deformation capacity of the retrofitted walls through out-of-plane testing. In all cases Triantafillou et al., (2017), Triantafillou et al. (2018), Gkournelos et al. (2020), and Karlos et al. (2020), the TRM system includes Expanded Polystyrene (EPS) as the insulation material. Mainly the authors have conducted experimental tests and provided results for the structural performance of the TRM system. Whereas the use of insulation material is primarily responsible for improving the thermal properties of the TRM system. Facconi et al. (2021) have used numerical models to evaluate the structural and thermal performance of the masonry structure retrofitted with the steel-TRM system with cement and insulation materials like aerogel, and light and heavy wood fiber. Whereas Longo et al. (2021) analyzed the structural (in-plane) and thermal (experimental measurements) of the masonry walls retrofitted with various configurations of TRM systems using glass fabric, steel fabric, natural hydraulic lime, and Geopolymer lime. As reported by the author, the geopolymer-based TRM system has higher ductility and improved thermal insulation capacity. Some interesting cases can be found in the literature, where Natural Fiber (NF) TRM systems have been used for masonry retrofitting/upgrading purposes. Notably, Menna et al. (2015) have used hemp fiber TRM, while Ferrara et al. (2020) have used flex fiber TRM, and Trochoutsou et al. (2021) have used two types of fibers flex and jute TRM for masonry retrofitting/upgrading, and authors only have reported the structural behaviors of the tested walls. However, no research works yet available in the literature highlighting the use of the NFTRM system, for the dual purpose of structural as well as thermal upgrading/retrofitting. The types of natural fibers, their origins, and possible applications for thermal and structural retrofitting are highlighted in Majumder et al. (2021). As reported in Townsend (2019), jute fiber accounts for about seven percent of the total global natural fiber production and is known to have good physical and mechanical properties. Whereas, other notable advantages and disadvantages can be found in Majumder et al. (2023). In the literature, various innovative applications of jute fiber-derived building materials can be found like jute composite mortars in Majumder et al. (2022a) and Majumder et al. (2024b), jute-FRP in Ascione et al., (2020), jute epoxy composite in Ferreira et al. (2016), jute fiber crude earth bricks in Saleem et al. (2016), jute fiber burnt bricks in Rashid et al. (2019), concrete retrofitting in Garikapati and Sadeghian (2020), etc.

The novelty of this research work is the use of the jute NFTRM system (with the use of the jute fiber products) for integrated (structural and thermal) upgrading/retrofitting systems for masonry. Notably, jute fiber nets (2.5 cm x 2.5 cm mesh type) and diatons have been used to enhance the strength of masonry wall, and the jute fiber composite mortar (with a combination of 30 mm fiber length and 1% of fiber with respect to the dry mortar mass) has been applied for thermal upgrading.

The paper is organized as follows: after introduction (section 1), in section 2 highlighting the materials used during this campaign, and then explains the methods used for various tests, thereafter results are discussed in section 3 and ends with final concluding remarks addressed in section 4.

2. Materials and methods

2.1. Materials

2.1.1. Jute raw fibers

Jute fibers (Figure 1.a) are collected from West Bengal, India. It is of Bangla Tosha - Corchorus olitorius (golden shine) origin. Physical and mechanical properties of the raw jute are reported in Majumder et al. (2022b), whereas the tensile strength, strain energy capacity, maximum axial strain, and Young's modulus are reported to be about 215 MPa, 0.8 kNmm, 0.013, and 17 GPa, respectively.

2.1.2. Jute fiber net

Two types of jute nets (Table 1) were fabricated using the class 1 mm jute thread. These nets have been applied to the masonry wall for structural upgrading. Mechanical properties, stiffness, strain energy capacity, maximum load capacity, and maximum displacement of jute fiber net (of configuration 2.5 cm x 2.5 cm) are found to be about 8 N/mm, 9 kNmm, 217 N and 73 mm, respectively, for details see Majumder et al. (2024).

Table 1. Jute fiber net configurations

	Dimensions	Mesh type
For structural test samples (Figure 1.b)	1m x 1m	2.5 cm x 2.5 cm
For thermal test samples (Figure 1.c)	0.9 m x 0.7 m	

2.1.3. Jute fiber made diatons

Transversal connectors or diatons (Figure 1.d) were used while upgrading/retrofitting the masonry wall to enhance the shear capacity and connect two surfaces of the NFTRM system. The physical and mechanical properties of these diatons are reported in Majumder et al., (2022b), and the tensile strength, strain energy capacity, and maximum axial strain are reported to be about 16 MPa, 14 kN.mm, and 0.03, respectively.

2.1.4. Mortar

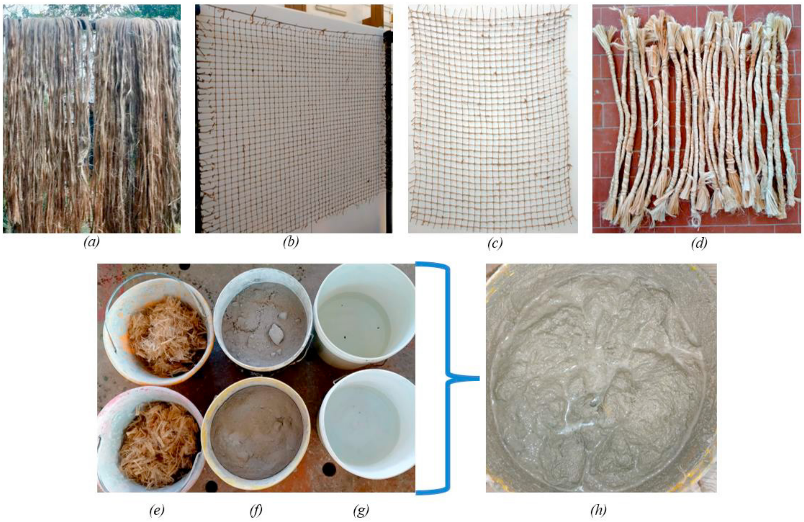
A cement-based mortar has been used during this campaign. It has been nominated as "Structural Mortar" (SM). It is classified as an M10 class, according to NTC, (2018). Its compressive strength, shear strength, and dry density are 10 MPa, 0.15 MPa, and 1545 kg/m3, respectively.

2.1.5. Jute fiber composite mortar

The jute fiber composite SM (Figure 1.h) has been prepared using 1% jute fiber (of 30 mm fiber lengths, Figure 1.e) with respect to the dry SM mortar (Figure 1.f) mass. While near about 30% of water (Figure 1.f) has been used based on previous, jute fiber physical tests, for details see Majumder et al. (2022b). The choice of fiber length and fiber percentage for the composite SM's grout (Figure 1.h) preparation has been considered based on (i) mechanical tests conducted on composite mortars with various fiber length and fiber percentage combinations, as reported in Majumder et al. (2023) and (ii) based on the EN 13501-1 (2019) standard, which states that the presence of fiber should not be higher than 1% in an incombustible composite mixture.

2.1.6. Hollow Brick

Semi-solid brick blocks/hollow bricks of Poroton Italia (2024) have been used for both unreinforced and upgraded masonry wall preparation. Bricks have the following specifications: dimensions of 300 mm × 250 mm × 250 mm, and a specific gravity of 800 ÷ 860 kg/m^3.


(a) (b) (c) (d)

(e) (f) (g) (h)

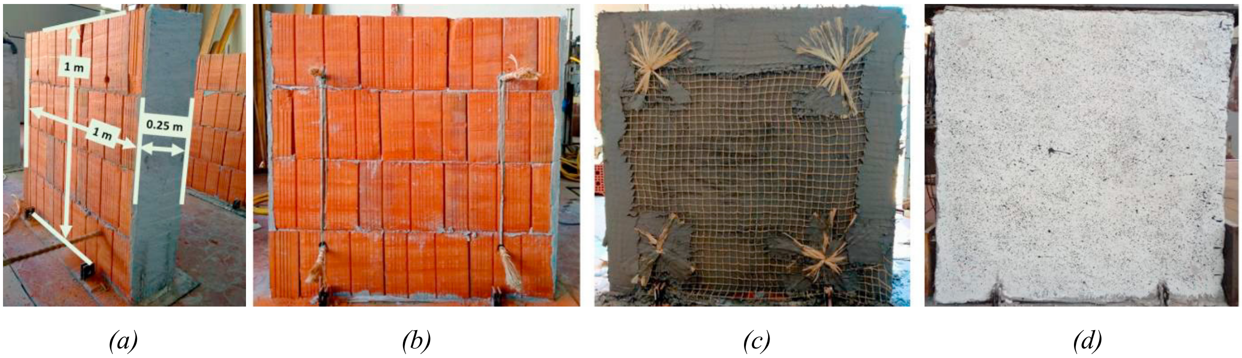
Figure 1. (a) Raw Jute fiber, (b) jute fiber net of “1 m x 1 m” dimension, (c) jute fiber net of “0.9 m x 0.7 m” dimension, (d) Jute fiber diatons, (e) 30mm Chopped jute fiber, (f) SM, (g) amount of water used, and (h) jute fiber composite SM.

2.2. Structural test wall preparation

After preparing the masonry wall (Figure 2.a), diatons are put through it (Figure 2.b). Thereafter, jute nets were placed on both sides of the wall and diatons were opened (Figure 2.c) and a thin layer of SM was applied, lastly the jute fiber composite SM (with the combination of 30 mm fiber length and 1% fiber with respect to the dry mortar mass) was applied on both sides (Figure 2.d) of the wall. Table 2 presents the specifications and configurations of the unreinforced and upgraded masonry walls.

Table 2. *Masonry wall specification and upgrading schemes.*

Masonry wall types (dimensions)	First mortar layer	Net Type	Total net used	Mesh type	Number of Diatons	Composite mortar used	Second mortar layer
HBW (Unreinforced) (1m × 1m × 0.25m)	SM	no	no	no	no	no	SM
HBW (Upgraded) (1m × 1m × 0.285m)	SM	1m × 1m	2	1.25 cm × 2.5 cm	4	SM + 1% (30mm) jute fiber w.r.t. mortar mass	



(a) (b) (c) (d)

Figure 2. Masonry wall (1m x 1m x 0.25 m): (a) drilling holes of diatons, (b) diatons placement, (c) nets application, (d) Upgraded wall.

2.2.1. In-plane cyclic tests

Figure 3 shows the in-plane cyclic test set-up of the upgraded masonry wall. A hydraulic jack has been used to apply a constant 40 kN vertical load on the masonry wall, corresponding to about 1% of the ultimate vertical load on the masonry wall.

The quasi-static load protocol is defined as follows: at first, the 40 kN vertical load was applied. Then the NFTRM upgraded masonry wall was subjected to the in-plane horizontal loads cycles, and for this purpose, three horizontal hydraulic jacks have been used. At first, the hydraulic jack nominated as H2 gets activated and thereafter H3 and the capacity of the wall samples was measured. After three consecutive load cycles, a monotonic growing horizontal load was applied to the wall, until collapse.

One 100 mm and two 50 mm transducers (nominal sensitivity of 2 mV/V, sensitivity tolerance ± 0.1%, and measurement resolution of 1 μm) were used to measure horizontal and diagonal displacements respectively.

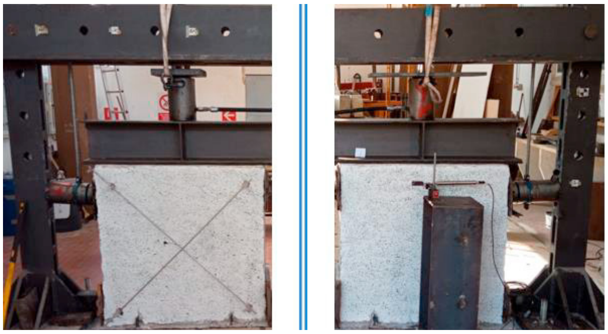

(a) *(b)*

Figure 3. Configuration for in-plane cyclic tests- (a) Front view and (b) Back view.

2.3. Thermal conductance test wall preparation

A masonry wall (0.9m x 0.7m) was prepared and diatons were put through it (Figure 4.a). Thereafter jute nets were placed on both sides of the wall and diatons were opened (Figure 4.b&c) and the thin layer of SM was applied, subsequently, the jute fiber composite SM (with the combination of 30 mm fiber length and 1% fiber with respect to the dry mortar mass) was applied on both sides of the wall (Figure 4.d&e).


(a) *(b)* *(c)* *(d)* *(e)*

Figure 4. (a) Diations are placed through the masonry wall, (b) Nets are placed, (c) Diatons are opened, and a layer of SM has been applied (d) Outer composite SM layer, and (e) Upgraded wall.

2.3.1. Thermal conductance tests

The climate chamber Biemme TH has been used for the thermal conductance tests. The instrument has been designed according to European regulation UNI EN ISO 6946 (2018) and it mainly consists of three parts (Figure 5.a,b & c). The NFTRM upgraded masonry wall sample (0.9m x 0.7m) was built on the fixed insulation wall (Figure 5.b), while two separate environmental conditions (cold side with 2°C, 50 RH% and 10.1m/s and hot side with 20°C, 50 RH% and 1.1m/s) were set for the two movable chambers. For the thermal conductance test, a flux sensor (with an integrated temperature sensor) with an accuracy of n 5% at T=20°C and a separate platinum temperature sensor of class A have been used (Figure 5.d). It was decided to collect temperatures (°C), humidity (RH%), and wind velocity (m/s) data at intervals of every 5 mins. Whereas a wireless (the ISM band of 2.4 GHz) system and a specific data logger with an integrated RAM have been used for collecting and saving data.

(a) (b) (c) (d)

Figure 5. (a) Hot chamber, (b) Central insulation wall and masonry wall samples, (c) Cold chamber, and (d) Installation of flux and temperature sensors.

3. Results

3.1. Integrated behavior

The integrated behavior of the masonry wall upgraded with the NFTRM system has been evaluated through in-plane cyclic tests (structural performance) and thermal conductance tests (insulation capacity).

3.1.1 Structural strength test

A constant vertical load of 40 kN has been applied on this wall. The in-plane cyclic tests were performed, and three load cycles were applied to the wall sample. Figure 6 represents the load-horizontal displacement graph until collapse.

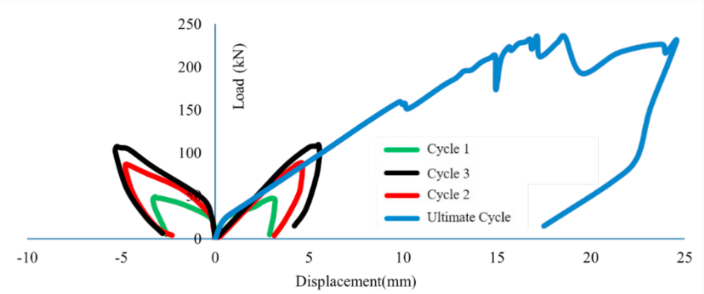


Figure 6. Load- Load-displacement graph of the in-plane cyclic tests.

The green, red, and black curves signify the measurements of the first, second, and third load cycles, respectively. Whereas the blue curve represents the ultimate load cycle, and the load was applied until the wall collapsed. The measured values can be negative or positive, and it depends on the applied force directions.

As can be seen in the graph (Figure 6), the wall structure has not shown exactly symmetrical behavior.

When the strength of the NFTRM upgraded masonry wall was compared with the un-strengthened masonry wall, it was observed that the load-bearing capacity (kN) of the strengthened wall had increased by more than 450%.

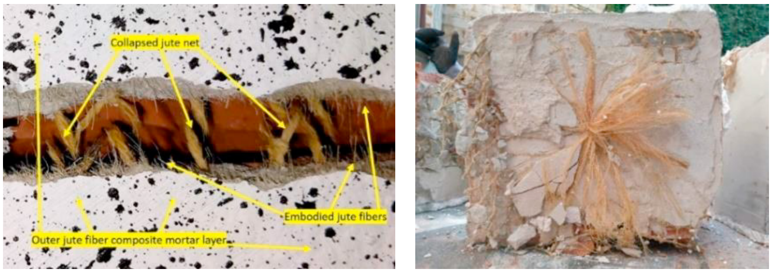
3.1.2. Thermal conductance test

Based on the measured data like the heat fluxes (W/m^2), the internal and external temperatures (°C), the thermal resistances of various layers of the masonry wall were calculated, and subsequently, the overall transmittance was calculated. Notably, the values were considered when the cumulative moving average of the heat fluxes (W/m^2), and internal and external temperatures (°C) were found to be in the range of ± 1% for at least consecutive 24 hours.

It can be observed that due to the application of the NFTRM system for upgrading the masonry wall, the insulation capacity of the wall has improved, as thermal transmittance (W/m^{2}K) reduced by approximately 36%, in comparison to the un-strengthened masonry wall.

3.1.3. Observations

Figure 7.a presents the internal structure of the masonry wall after the collapse, it is clearly visible that at and along the crack, the net was ruptured, while on the edge of the crack line, the jute fibers are noticeable. Therefore the increase in the strength of the NFTRM upgraded masonry wall was induced due to the presence of nets on both sides of the masonry wall, as well as the presence of embodied fibers also helped in carrying the applied loads, as already proved by the authors in (Majumder et al., 2023). Figure 7.b shows one part of the internal upgrading scheme with jute fiber products (jute net and diaton) after the wall sample's demolition.



(a) *(b)*

Figure 7. (a) Crack pattern after the collapse, and (b) Internal upgrading scheme of a part of the wall, after demolition.

4. Conclusion

Integrated retrofitting could be an ideal solution for mitigating the masonry structures/buildings' seismic vulnerability and enhancing thermal performance. Nevertheless, a balance between structural strength and insulation capacity point needs to be regimented for an acceptable integrated solution, keeping in mind both seismic and energetic standards. This paper focuses on the integrated upgrading or retrofitting of the masonry wall with a Natural Fiber (NF) Textile Reinforced Mortar (TRM) system. Various jute fiber products (like fiber nets, diatons, and jute fiber composite mortars) have been used for NFTRM upgrading or retrofitting purposes.

The proposed jute NFTRM system was demonstrated to be effective both for:

- The load-bearing capacity (kN) increased by more than 450%, in comparison with the un-strengthened wall.
- The insulation capacity improvement, with the reduction of thermal transmittance (W/m^{2}K) value by about 36%, for the upgraded masonry wall, with respect to the un-strengthened one.

Further research activities are scheduled to retrofit the same masonry wall with other types of natural fibers with different net mesh configurations and another composite mortar composition.

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