OUT-OF-PLANE BENDING STRENGTH OF LIGHTWEIGHT MASONRY WALLS STRENGTHENED BY COCONUT ROPE NETTING

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Abstract

This paper presents the effectiveness of employing of coconut rope netting reinforcement on lightweight brick masonry walls. The lightweight brick was developed with a mixed design of cement: sand: coconut fiber: water: foam of 1.0:0.985:1.5:0.55:0.007 by weight. The strengthened wall panels were prepared by applying coconut rope netting with various external reinforcing patterns to the walls. Four types of coconut rope netting were employed to examine the effects of reinforcement ratio. The performance of the walls reinforced with coconut fiber was assessed by conducting experimental tests. This was to measure the out-of-plane bending strength, the deformation capacity, and the features of the failure. The test result indicated that the primary cause of failure for coconut fiber reinforced masonry walls is the flexural instability, which leads to the formation of small-scale crack patterns in the walls. The highest improvement was achieved when the reinforcement ratio reached 5.5%. This resulted in a significant increase of 114.97% and 44% in the load-bearing capacity and the ductility index, respectively. The comparisons between the experimental and the analytical results for the out-of-plane bending resistant of the walls revealed that the suggested analytical model offers a reasonable estimation. Hence, the utilization of coconut rope netting demonstrates the satisfactory enhancement, and it contributes to the advancement of sustainable and cost-effective construction technique.

Keywords: Lightweight brick masonry walls; Out-of-plane bending strength; Load bearing capacity; Ductility index; Coconut rope netting

Introduction

A magnitude 6.3 earthquake struck Chiang Rai Province in Thailand on May 5, 2014, resulting in substantial devastation, particularly to brick wall structures. The earthquake exposed the insufficient shear and bending strength of masonry walls, which failed in-plane and out-of-plane (Kadam *et al*., 2014; Leeanansaksiri *et al*., 2018).

Fiber-reinforced polymer (FRP) composites have been extensively employed in recent decades to improve the durability of existing building structures. Glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) are common FRP materials that enhance the capacity of masonry walls to withstand shearing and bending

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forces (Hasim *et al*., 2020). FRP materials have significant drawbacks, including high costs, limited fire resistance, and an environmental impact, despite these advantages (Bisby *et al*., 2005; Sen and Reddy, 2011). Furthermore, FRP composites demonstrate inadequate compatibility with brick surfaces, particularly when subjected to elevated temperatures, resulting in a degradation of mechanical properties (Valluzzi *et al*., 2014; Reem Bitar *et al*., 2020; Abdulla *et al*., 2021; Cima, 2022).

In order to overcome these constraints, researchers have investigated the utilization of natural fibers as sustainable substitutes for synthetic fibers in the reinforcement of structures. Natural fibers, including sisal, bamboo, jute, and hemp, have demonstrated commendable mechanical properties, exceptional thermal insulation, and environmental advantages (Yannas, 2001; Felice *et al*., 2014). Coir textiles are becoming increasingly popular due to their eco-friendliness and high tensile strength. Research has shown that the out-of-plane flexural strength of masonry walls can be substantially enhanced by natural fibers such as hemp (Faruk *et al*., 2014).

The potential of coconut fiber as a reinforcement material is evident in its high lignin content and strength. Khan *et al*. (2012) have found that coconut fibers retain 80% of their tensile strength even after being submerged in soil for six months. Their mechanical properties are comparable to those of glass fibers, rendering them a viable alternative for reinforcing structures (Nam *et al*., 2011). In comparison to synthetic insulating materials, coconut fibers also possess exceptional thermal insulation properties, which can mitigate their environmental impact (Doukas *et al*., 2006; Manohar, 2012).

The inherent heterogeneity and concerns about durability of natural fibers present challenges in structural applications, despite their advantages (Baruah and Talukdar, 2007; Munawar *et al*., 2007). Research has emphasized the challenges associated with assessing the influence of natural fibers on the performance and blending of concrete. For example, Yan and Chouw (2013) discovered that the incorporation of coconut fibers into concrete mixtures resulted in an increase in compressive strength and ductility, thereby illustrating the potential of natural fibers to enhance concrete structures.

Ali *et al*. (2012); Baruah and Talukdar (2007) have both emphasized the extraordinary tensile strength and resilience of coconut fibers in challenging conditions. Compressive and flexural strength have been significantly enhanced by the incorporation of coconut fibers in studies conducted using X-ray electron microscopy (Khan and Ali, 2019). The ecological advantages of utilizing natural fibers, which are frequently regarded as waste materials, further endorse their use in construction.

None of the previous research has investigated the use of coconut fibers for the reinforcement of masonry walls, exceptionally for the out-of-plane flexural strength. Therefore, the purpose of this study is to evaluate the flexural strength of unreinforced masonry (URM) walls that have been externally reinforced with natural coconut rope netting. The investigations include the behavior of wall specimens under loading, crack patterns, reinforcement efficacy, and the flexural strength in various configurations. The research endeavors to address the voids in existing knowledge and emphasize on the novelty of utilizing coconut rope netting for the external reinforcement of masonry walls by concentrating on these aspects.

Experimental Program

Mixed Design of Lightweight Concrete Blocks

The wall is constructed with lightweight concrete blocks that are made by mixing Type 1 Portland cement, fine sand, coconut fibers, water, and foam. The ratios of these elements were tuned to fulfill the specifications of lightweight concrete blocks as per. ASTM C567/C567M-19 (2019). Table 1 displays the configuration of the experimental arrangement in the laboratory. The mixed design for the lightweight concrete blocks incorporates a constant quantity of cement, while the sand is partially substituted with coconut fibers at ratios varying from 0-2% of the fine sand weight. The quantities of water and foam ranged from 0.50-0.75 and 0.005-0.009, respectively, based on the weight of the cement. The concrete specimens were tested to determine their compressive strength, density, water absorption, and flexural strength. The samples used for testing had dimensions of 5×5×5 cm and 16×4×4 cm, and the tests were conducted in accordance with the standards ASTM C642-97 (1997); ASTM C109/C109M (2002); ASTM C348 (2017), respectively.

The first experimental mixture sought to ascertain the appropriate proportions of coconut fibers and sand. The findings obtained from the initial mixture were utilized to establish the moisture content for the subsequent mixture. The second experimental mixture determined the ideal amount of water, which was then used to calculate the foam content for the third mixture. These findings led to the final proportions of the mixture, as displayed in Table 1.

Table 1. Proportions of Lightweight Concrete Block % by Weight

Mix ID	Cement (%)	Sand (%)	Coconut Fibers (%)	Water (%)	Foam (%)
C0	1.0	1.0	0	0.50	0.005
C0.5	-	0.995	0.5	-	-
C1.0	-	0.990	1.0	-	-
C1.5	-	0.985	1.5	-	-
C2.0	-	0.980	2.0	-	-
C2.5	-	0.975	2.0	-	-
C1.5	1.0	0.975	1.5	0.50	0.005
-	-	-	-	0.55	-
-	-	-	-	0.60	-
-	-	-	-	0.65	-
-	-	-	-	0.70	-
-	-	-	-	0.75	-
C1.5	1.0	0.985	1.5	0.55	0.005
-	-	-	-	-	0.006
-	-	-	-	-	0.007
-	-	-	-	-	0.008
-	-	-	-	-	0.009
C1.5	**1.0**	**0.985**	**1.5**	**0.55**	**0.007**

Test specimens

During the testing phase, various wall reinforcing patterns were established according to the cross-sectional area, volume, and density. There were four different reinforcement configurations, each consisting of a single layer of coconut rope netting reinforcement. The coconut rope used in this study was factory-made in Thailand, with a diameter of 0.5 cm, and was hand-netted into a 20 mm ×20 mm mesh. The fibers underwent a treatment process involving immersion in sodium hydroxide solution with a pH adjusted to 12-12.5 for a period of 168 hours. Subsequently, they were subjected to baking at a temperature of 60 degrees Celsius for a duration of 72 hours. The evaluated behaviors encompassed the out-of-plane flexural strength, maximum load-bearing capacity, ductility, and energy absorption capabilities of the lightweight concrete block walls that were reinforced with coconut rope netting. Three samples were examined for each reinforcement design, with unreinforced walls acting as control samples labeled C0, as depicted in Figure 1(a). There were four different reinforcement configurations.

- C1 Diagonal Reinforcement: Reinforced with two diagonal and one transverse coconut rope netting on both sides, as shown in Figure 1(b).

- C2 Two-Strips Reinforcement: Reinforced with two longitudinal and three transverse coconut rope netting on both sides, as shown in Figure 1(c).

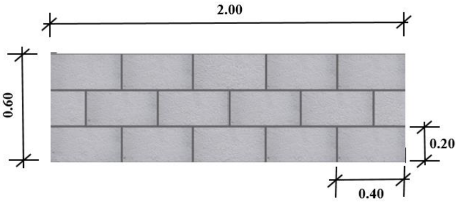
- C3 Three-Strips Reinforcement: Reinforced with three longitudinal and two transverse coconut rope netting on both sides, as shown in Figure 1(d).

- C4 Full-Sheet Reinforcement: Reinforced with one 60x200 cm coconut rope netting on both sides, as shown in Figure 1(e).

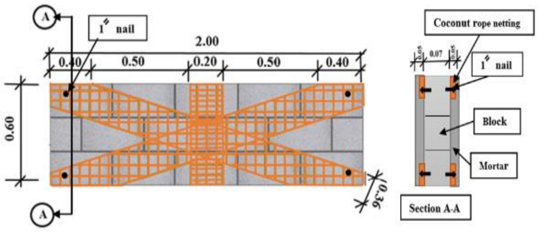
The procedure to strengthen the walls is as follows: the coconut rope netting is securely overlayed to the wall with the adhesive cement. Subsequently, 1-inch nails are employed to fasten the mesh at all four corners. Finally, the walls are plastered on both sides with a 5 cm thick layer of mortar. This is to investigate the effectiveness of using nails and adhesive mortar to mitigate the slippage between the coconut rope netting and the wall. The details of each test wall pattern are shown in Table 2, including the basic properties of the coconut rope netting in each pattern and the unit weight of the coconut rope netting relative to the wall area.

The walls were built using lightweight concrete blocks that were blended with coconut fibers. Each block had dimensions of 20×40×7 cm and covered an area of 800 cm^2. The walls were constructed with dimensions of 7×200 cm for thickness and length, and a height of 60 cm. The walls were built using a running bond design, which ensured that the joints were aligned with the outer surfaces of all the brick units. The walls were left to undergo the process of curing in the open air for a period of 28 days prior to test.

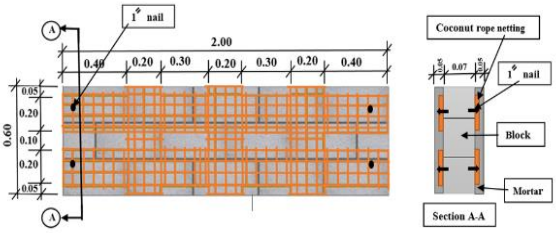
The utilization of nails and adhesive cement is required to guarantee that reinforcements are firmly affixed to the wall, as stated in the specifications. This improves the stability and overall efficiency of the structure.



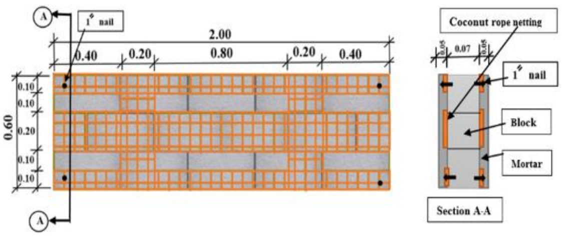
(a) Lightweight concrete block wall without coconut rope netting reinforcement (C0)



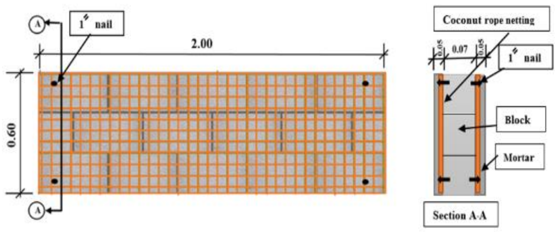
(b) Lightweight concrete block wall with diagonal coconut rope netting reinforcement (C1)



(c) Lightweight concrete block wall with two-strip coconut rope netting reinforcement (C2)



(d) Lightweight concrete block wall with three-strip coconut rope netting reinforcement (C3)



(e) Lightweight concrete block wall with full-sheet coconut rope netting reinforcement (C4)

(f) View of samples

Figure 1. The control wall configuration and the different coconut rope netting reinforcement

Table 2. **Proportions of Lightweight Concrete Block % by Weight**

Series	Weight (g)	Cross-sectional area of mortar (cm^2)	W_m (g/cm^2)	A_{sf} (cm^2)
C1	495.7	1,020	0.041	14.790
C2	562.2	1,020	0.047	17.340
C3	628.7	1,020	0.052	19.300
C4	660.8	1,020	0.055	19.890

Where W_m is the unit weight of mesh calculated from the weight ratio of coconut rope netting to the wall area being reinforced, and A_{sf} is the effective area of reinforcement for mesh layer.

These standards enhance uniformity in usage, minimize mistakes, and guarantee that the reinforcements function as intended when subjected to stress, so enhancing reliability.

Material properties

The laboratory experiments were performed to assess the compressive strength of the mortar, the compressive strength of the brick prisms, and the characteristics of the coconut rope netting in order to investigate the mechanical properties of the materials utilized in the masonry wall testing. In order to maintain uniform characteristics among all wall samples, all tests were conducted on the same day as the wall testing. The mean compressive strength of the brick prisms was 3148 MPa The mean compressive strength of the 5×5 cm mortar samples was 4326 MPa, whereas the mean tensile strength of the mortar was 7.224 MPa. A Universal Testing Machine (UTM) was used to evaluate the mechanical properties of the coconut rope netting, which had a diameter of 0.5 cm. The testing was conducted at a loading rate of 1 mm/min. The tests are depicted in Figure 2. The mean values obtained from five tests indicated a maximum tensile strength of 15.57 MPa and a modulus of elasticity of 29.33 MPa. The mechanical qualities are specified in Table 3.

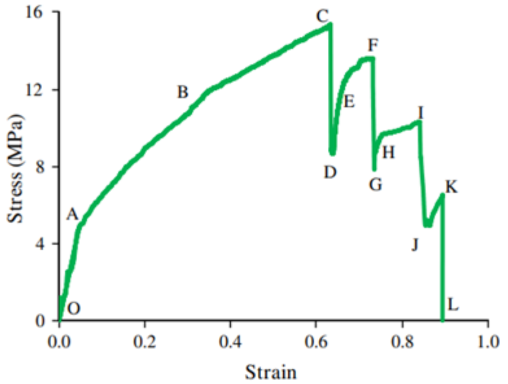
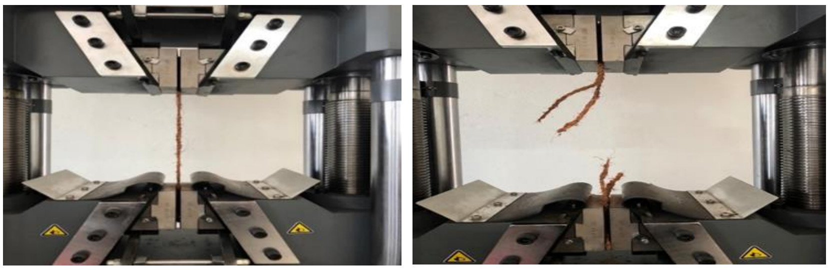


Figure 3. **Typical stress-strain relationship for coconut rope netting**



(a) Tensile strength test of coconut rope

(b) Molding of lightweight concrete blocks

Figure 2. **The control wall configuration and the different coconut rope netting reinforcement**

Table 3. The results of the material properties testing conducted during the experiments

f'_c (MPa)	f'_m (MPa)	f_{tm} (MPa)	E (MPa)	f_{tc} (MPa)
3.148	4.326	7.224	29.33	15.75

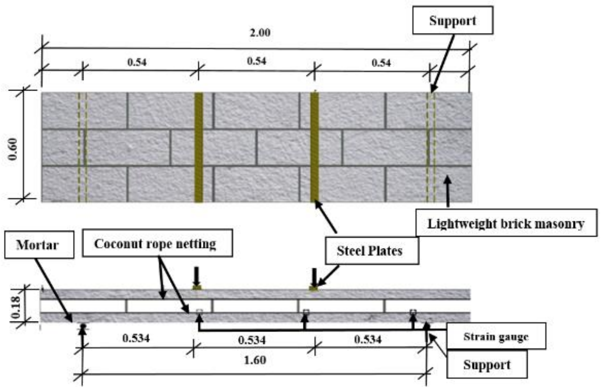
Where f'_c, f'_m, f_{tm}, E, f_{tc} are the compressive strength of concrete blocks, the compressive strength of mortar, the tensile strength of mortar, modulus of elasticity of wall, tensile strength of coconut coir, respectively.

Testing procedure

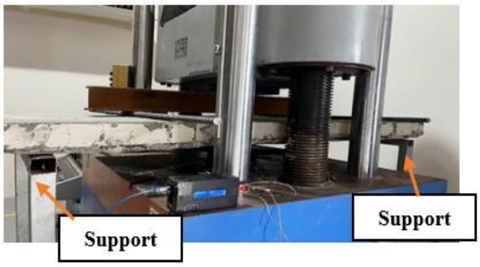
The bending strength of the walls was evaluated by subjecting it to a four-point bending test using a machine that complies with ASTM D6272-17 (2020) requirements. During the test, the sample walls was subjected to loads until it deflects and fails as a result of bending stress. The test involved observing changes and recording load values at various intervals of the sample. Data was gathered through the utilization of installed measuring devices that are linked to a data logger. Subsequently, the data logger was connected to a computer to facilitate the collecting of data. Strain gauges were placed at regular intervals on the coconut rope netting in the compression zone, shear zone, and tension zone to measure the strain at these locations. Wall deflection was measured to examine the flexural capacity, ductility, and failure mechanism at the indicated sites. Both the fracture pattern and the mode of failure were documented prior to, during, and after the test. The objective of this technique is to comprehend the behavior of the wall being tested and document its features, such as cracks and failures. Figure 4 depicts the methodology for evaluating the wall bending strength using a four-point bending testing machine, as well as the specific installation placements of different equipment.

The utilization of specific reinforcement patterns is intended to examine various wall reinforcement techniques and evaluate the load-bearing capabilities of each type of reinforcement.

Strategically positioning strain gauges is essential as it enables accurate assessment of deformation and stress in vital sections of the structure. By placing them at these specific locations where forces directly impact the supports, it becomes possible to gather pertinent data regarding the structural response to external loads, evaluate the performance of the structure, and thoroughly confirm the efficacy of the reinforcement.



(a) Wall Bending Strength Testing Model



(b) Wall Bending Strength Testing

Figure 4. The method for testing the bending strength of the wall

Analytical modelling

The analysis of the model for calculating the load-bearing capacity of brick walls made with lightweight aggregate blocks, reinforced with coconut rope netting, both with and without coconut rope netting, can be summarized as follows.

Un-strengthened walls

The maximum moment capacity of the control specimens without reinforcement is determined by the modulus of rupture (f_r) of the brick units. The modulus of rupture for concrete masonry units is calculated according to ACI 318-19 (2019), where the compressive strength of the mortar (f'_m) is obtained by the mortar prism tests.

$$f_r = 0.62\sqrt{f'_m} \quad (1)$$

Then, the cracking moment of the mortar (M_{cr}) can be calculated by Equation 2

$$M_{cr} = \frac{f_r b h^3}{12c} \quad (2)$$

Where b and h are defined as the width and height of the brick wall, respectively, and c is the distance from the neutral axis to the tension face. To ensure accuracy, the likelihood of cracks occurring in unreinforced walls was tested according to the standards set by the American Concrete Institute (ACI 318-19, 2019).

Coconut rope netting -strengthened walls

To determination the ultimate bending strength of the masonry wall reinforced with coconut rope netting, the following assumptions were considered: (1) the strain variation across the wall section was linear. (2) the tensile strength of the brick was neglected. (3) the brick wall and the coconut rope netting are completely composited, therefore the strain of both materials are consistent. The distribution of compressive forces exerted on rectangular blocks is 85% of the highest compressive force applied, as presented in Figure 5.

The value of T_f is determined by a calculation.

$$T_f = A_{sf} . f_{yf} \quad (3)$$

Where f_{yf} is the tensile strength of the coconut rope; A_{sf} is the effective area of reinforcement for layer i of the mesh, which is obtained from:

$$A_{sf} = \eta V_f A_c \quad (4)$$

Where η is the efficiency factor of the expanded metal mesh reinforcement, which can be taken as 0.65 according to ACI 549.1R-93 (1999); V_f is the ratio of the volume of reinforcement for layer i, $V_f = \frac{V_m}{V_c}$; $V_m = N W_m A_c$, $V_c = \gamma_m h A_c$, where, N is Number of mesh layers, h is the thickness of ferrocement, W_m is the unit weight of mesh, γ_m is the density of steel, A_c is the cross-sectional area of the mortar; d_f is the effective depth of the strengthened brick wall; and h depending on the equilibrium of forces where the depth of the compressive stress block is defined as follows:

$$a = \frac{A_{sf} f_{yf}}{0.85 f'_c b} \quad (5)$$

The maximum flexural(M_n) capacity can be determined by

$$M_n = A_{sf} . f_{yf} \left(d_f - \frac{a}{2}\right) \quad (6)$$

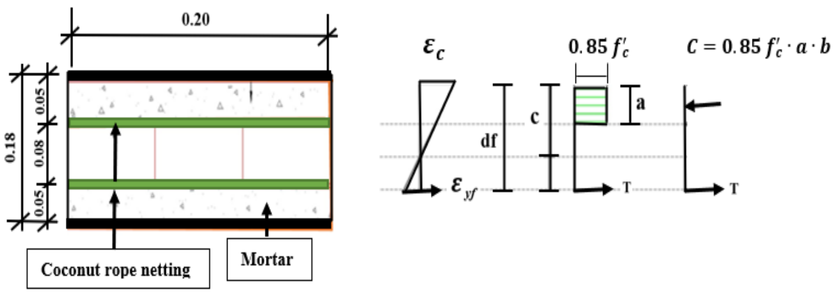


Figure 5. Free body diagram of the cross section of masonry wall strengthened with coconut rope netting

The assumption that the strain variation in the wall section is linear means that the strain distribution varies from compression on the top side to tension on the bottom side of the wall section. While, the coconut rope deforms the same amount as the attached brick wall, which also subject to tension. Therefore, the brick wall and the coconut rope netting are completely composited. The assumption of linear stress fluctuation in the wall section implies that the stress distribution across the wall section changes uniformly from one edge to the other. Assuming linearity simplifies the analysis and allows for the calculation of stress and strain distributions, hence enhancing the comprehension of the wall's reaction to different loading circumstances. This assumption is essential for determining the response of reinforced composite walls to bending and other pressures. It helps in confirming experimental results and comparing them with theoretical expectations.

The results are utilized on an analytical model employed to forecast the behavior of reinforced composite walls under different loading circumstances. This entails analyzing the structural behavior of the walls under various forces, including bending, shear, and axial loads. The model facilitates comprehension of the dispersion of stress and strain inside the walls, enables identification of probable places of failure, and allows for evaluation of the overall stability and performance of the structure. Incorporating these estimates into the design process enables modifications in reinforcement patterns, material choices, and reinforcement procedures to guarantee the walls can securely endure the expected loads. The ability to forecast is essential for the creation of more long-lasting buildings.

The research aimed to forecast the capacity of walls to withstand bending forces in a direction perpendicular to the plane, with the objective of enhancing their flexibility. This was achieved by reinforcing the walls with coconut rope mesh, which provides ductility. This intervention serves to postpone the structural collapse of walls impacted by seismic activity.

Experimental test results

Failure modes

According to the experiment, the wall samples failed because they were unable to endure the increasing load. The test findings for each wall reinforcing design, along with the failure patterns shown in Figure 6, are shown in Table 4. Figure 6 illustrates the various modes of failure seen in the four reinforcing configurations employing coconut rope netting. Cracks first appeared at the cement joints around the upper edges of the unreinforced sample and then spread horizontally. The fractures expanded in direct proportion to the force applied, leading to structural failure and exposing the load-bearing capability of the C0 wall. Figure 6(a) exhibits the pattern of cracks.

The wall sample, which was not strengthened, experienced failure when subjected to a load of only 6. 77 kN, resulting in a deflection of 7 millimeters. The failure patterns found for all samples of reinforced walls were as follows: (1) Upon application of the load, the walls experienced bending moments, resulting in cracks forming near the middle of the wall; (2) The walls had the greatest shear stress at the cross- section, with cracks expanding and extending upwards as the load rose, which could be observed from the bottom of the wall. As a result, the coconut rope netting broke and the fractures spread to the top of the wall, leading to the failure of both the wall and the coconut rope netting as the maximum load-bearing capability rose with the reinforcement ratio for designs C1 to C4, reaching 10. 77, 12. 70, 13. 83, and 14. 54 kN. correspondingly. The deflection values for each configuration were 9, 11, 13, and 14 mm, respectively, as shown in Figure 6(b) depicting the corresponding crack patterns.

Research has revealed that as the reinforcement ratio is augmented, there is a corresponding increase in both the strength and deformation capacity.

Table 4. Summary of experimental results for tested specimens

Specimen	Ultimate Load (kN)	Ultimate Midspan Deflection (mm)	Failure Mode
C0 Control	6.77	7	Flexure
C1 diagonal	10.77	9	Flexure with failure of coconut rope netting
C2 three tripes	12.70	11	Flexure with failure of coconut rope netting
C3 two stripes	13.83	13	Flexure with failure of coconut rope netting
C4 full sheet	14.54	14	Flexure with failure of coconut rope netting

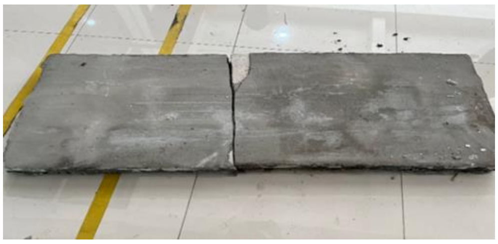
Load-deflection behavior

Based on the graph in Figure 7, which shows the correlation between the applied load and the maximum deflection of the wall, it can be noted that the wall displays a bilinear behavior. During the initial stage, the wall begins to bear the imposed load without any apparent cracks, exhibiting a consistent response until the first crack emerges at approximately 12-15% of the maximum load. The initial fracture occurs near the midpoint of the bottom of the wall, precisely where the largest tensile stress is present (below the neutral axis). As the fracture develops, the gradient of the graph lowers, signifying the shift to the second linear phase.

During the second phase, the wall undergoes heightened cracking in the regions that have been strengthened with the coconut rope netting. These cracks continue to spread and proliferate until the mesh eventually gives way. Currently, the graph experiences a rapid decrease in slope as the wall approaches its maximum load capability. The decrease in slope is equal to 36 %. Once the peak is reached, the wall is unable to bear any more load, causing the deflection to steadily rise until it ultimately fails.

The maximum deflection has a positive correlation with the quantity of reinforcement provided by the coconut rope netting. This is apparent from the graph, which displays a more extended horizontal section, indicating a continuous and sustained deflection. The average maximum deflection for the control wall (C0) is approximately 7 mm. The walls reinforced with C1, C2, C3, and C4 exhibit increasing maximum deflections of 9 mm, 11 mm, 13 mm, and 14 mm, respectively.

This discovery has important consequences for the field of structural engineering and construction practices, namely in enhancing the performance of walls by slowing down the process of failure through improved ductility. The stiffness and ductility index values were determined by calculating the area beneath the load- deflection graph.



(a) C0

(b) C1

(c) C2

(d) C3

(e) C4

(f) Enlarged View of Out-of-Plane Flexural

Figure 6. Cracks in a brick and block wall reinforced with coconut rope netting

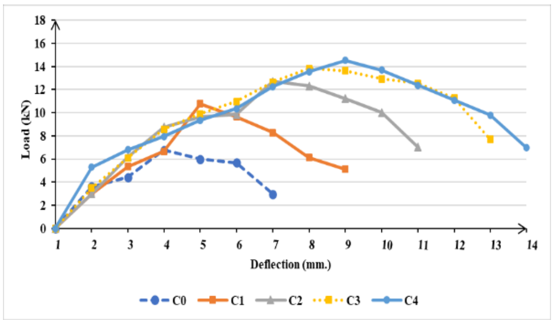


Figure 7. Relationship of load and wall deflection

Wall capacity

The load-bearing performance of the wall clearly demonstrates that the out-of-plane flexural strength of the wall much improves with a greater reinforcement ratio. The unreinforced control wall sample experienced failure at a lower applied stress and showed minor displacement. Figure 8 indicates the correlation between the coconut rope netting reinforcement ratio (Wm) and the increase in out-of-plane flexural capacity of the wall samples.

The C1 structure had a reinforcement ratio of 4.10% that led to a 59.15% improvement in out-of-plane flexural strength compared to the unreinforced control wall (C0), the C2 configuration, which had a reinforcement ratio of 4.70%, exhibited a significant 87.75% enhancement in flexural capacity. The C3 configuration, which had a reinforcement ratio of 520%, showed a significant 104.38% improvement in flexural strength. Finally, the C4 configuration, which had a reinforcement ratio of 5.50%, showed a significant 114.97% improvement in its ability to resist bending in the out-of-plane direction.

The utilization of coconut rope netting reinforcement significantly increased the flexural capacity of the wall in the out-of-plane direction, achieving a remarkable enhancement of up to 114.97% when compared to the control sample without any reinforcement. The reinforcement ratios (Wm) varied between 4.10% and 5.50%, leading to a flexural strength increase ranging from 59.15% to 114.97% relative to the control sample. The graph depicted in Figure 8 illustrates a direct correlation between the reinforcement ratio (Wm) of the coconut rope netting and the enhancement in the out-of-plane flexural strength of the wall, as compared to the wall sample without any reinforcement.

The study found a positive correlation between the reinforcement ratio of the wall and its flexural strength, indicating that as the reinforcement ratio increases, the flexural strength also increases. The reason for this is that the flexural capacity is directly related to the different configurations, which increase the cross-sectional area of the reinforcement material depending on the arrangement pattern.

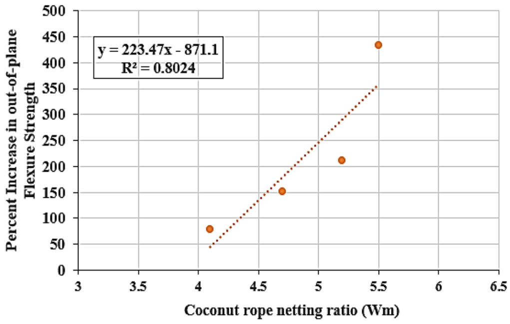


Figure 8. Relationship between the coconut rope netting reinforcement ratio and the out-of-plane flexural strength of the wall

Ductility index

In order to assess the ductility of the walls that were reinforced with coconut rope netting we employed the fracture energy or absorbed energy method. Fracture energy is the measure of the energy that is absorbed by the test specimen until it reaches the point of failure. The total absorbed energy by the wall, which represents the load-deflection energy response, is calculated by determining the area under the curve. The ductility index, defined as the ratio of the fracture energy of the reinforced wall to the fracture energy of the unreinforced wall, serves as a measure of the effectiveness of the coconut rope netting in providing reinforcement.

Figure 9 displays the energy absorption and ductility values, which are determined by the reinforcement patterns of the walls. The findings suggest that the ductility of the material increases as the reinforcement ratio increases. These findings indicate that increasing reinforcement ratios result in increased energy absorption by the test specimen, necessitating a higher amount of energy to induce wall failure. In addition, despite the fact that the C3 and C4 wall sets exhibit nearly identical reinforcement ratios, there is only a minor disparity in their ductility values. The walls exhibit gradual deformation prior to failure, and the use of coconut rope netting as reinforcement leads to an increase of the energy absorption and the ductility of the wall. It can be observed that the relationship between the reinforcement ratio (W_m) and the energy absorption is linear, as well as that of the ductility.

It has been shown that there is a positive correlation between the amount of absorbed energy and the ductility index.

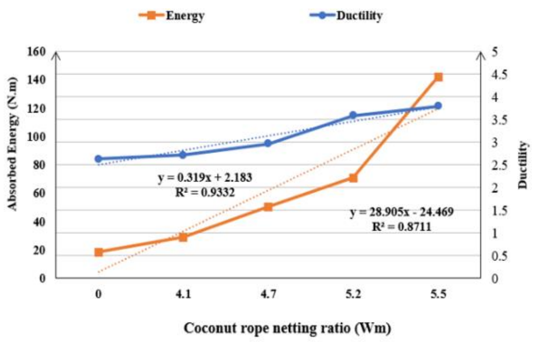


Figure 9. Relationship between coconut reinforcement ratio and energy absorption as well as the ductility

Performance of analytical model

Un-strengthened walls

The moment capacity of the control wall was calculated by Equation (2) and compared with the test result. The value obtained from equation 2 is 1.153 kN-m, whereas the test yielded a capacity of 1.204 kN-m. There is a discrepancy of 4.24% between both of these values, which is not exceed 11%, as per ACI 318-19. This investigation has a resemblance to the study conducted by Reem Bitar *et al*. (2020).

The values acquired from the basic tests, which were used as data for calculations according to ACI 318-19, have been determined to be valid for use in calculations.

A higher ductility index enhances the overall strength and resilience of a structural system. As the ductility index increases, the structural wall system becomes more ductile, resulting in a slower failure process. The ductility index is a reliable measure of the effectiveness of coconut rope mesh reinforcement in improving the seismic resistance of walls. Increased reinforcement with coconut rope netting raises the ductility index, thereby enhancing the wall's earthquake resistance.

Coconut rope netting-strengthened walls

The moment capacity of the walls, which were reinforced with coconut rope netting was determined using the methodology outlined in Section 3.2 of this research. Equation (6) was employed to ascertain the utmost moment capacity for every wall arrangement: C1, C2, C3, and C4. The procedure to compare the results of the analytical model and the experimental data is as follows:

- For the unreinforced specimen (C0), the cracking moment (M_{cr}) is calculated according to Equation 2.
- For the reinforced specimens C1-C4, the moment capacity is calculated according to Equation 6, where the value of A_{sf} is determined from Equation 4.
- The calculated moment of each specimen (C0, C1, C2, C3, C4) are 1.153, 2.859, 3.275, 3.678, 3.767 kN-m, respectively. While, those of the experimental results are 1.404, 2.871, 3.387, 3.687, 3.878 kN-m, respectively.

Figure 10 presents a comparison between the test results and the calculated values for all reinforcement configurations. Upon comparing the predicted flexural strength with the values obtained from the tests, it was observed that the calculated values for configurations C1, C2, C3, and C4 were lower by 0.4%, 3.3%, 0.24%, and 2.86%, respectively. The suggested model accurately predicts the load-carrying capability of walls.

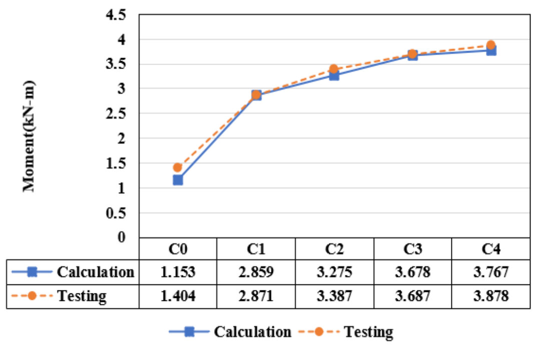


Figure 10. A comparison of the moment values obtained from Equation (6) with the test

Figure 11 depicts the correlation between the applied load and the strain. The strain gauge results demonstrate that the elongation characteristics of the coconut rope netting closely align with its tensile strength. The study revealed that the stretching characteristics of the coconut rope netting (C4) closely corresponded to its maximum tensile strength of 13.8 kN. The tensile strength of the coconut rope netting itself was found to be approximately 15.75 kN. as shown in Figure 3

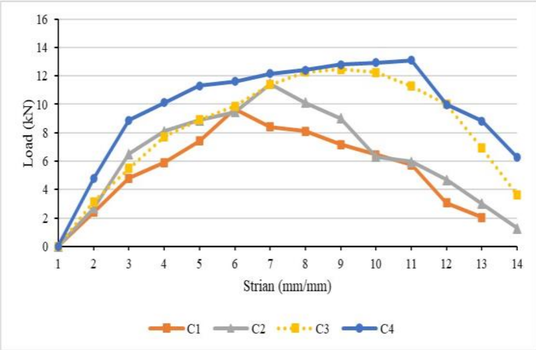


Figure 11. Relationship between Load and Strain Gauge

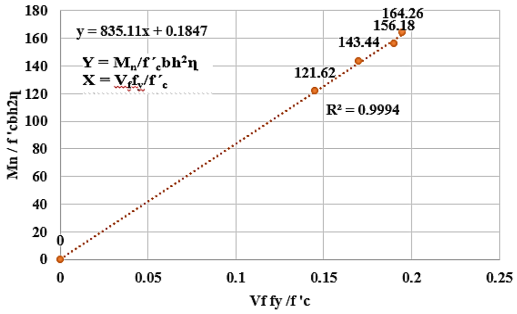


Figure 13. Bending strength per amount of reinforcement using coconut rope netting

Figure 12 shows the stiffness values associated with each reinforcement arrangement utilizing coconut rope netting. The stiffness values were calculated by determining the slope of the load-deflection curve at which the specimen failed. The stiffness values for configurations C0 through C4 are 1.96, 2.45, 2.8, 3.27, and 5.45, respectively. It was noted that the stiffness values exhibited a direct correlation with the reinforcement ratio of the coconut rope netting.

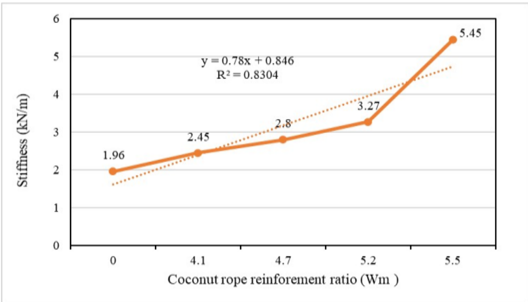


Figure 12. The strength values of all forms of reinforcement with coconut rope netting

To predict the moment capacity of the strengthened brick wall, the non-dimensionless parameters for correlating the flexural capacity and the reinforcement quantity of the coconut rope netting are proposed in terms of $\frac{M_n}{f_c' bh^2\eta}$ and $\frac{V_f f_y}{f_c'}$, respectively. The relationship between the moment capacity and the volume of reinforcement of the coconut rope netting can be visually depicted using $\frac{V_f f_y}{f_c'}$ on the x-axis and $\frac{M_n}{f_c' bh^2\eta}$ on the y-axis, with reference to ACI 549.1R(1999). This is depicted in Figure 13.

It has been noted that when the volume of reinforcement is increased using coconut rope netting there is a commensurate rise in the moment capacity. The moment capacity of the strengthened brick wall may be determined from the following equation:

$$\frac{M_n}{f_c' bh^2\eta} = 835.11\frac{V_f f_y}{f_c'} + 0.1847 \qquad (7)$$

The moment capacity of the reinforced brick wall can be calculated using Equation 7. This equation allows us to anticipate the flexural moment capacity by substituting the appropriate values.

The limitation pertains to the difficulties involved in physically fabricating and affixing the coconut rope netting utilized for reinforcement. The manual creation of these components can result in discrepancies in their application, thereby affecting the consistency and efficacy of the reinforcement. The fluctuation can impact the performance of the walls, leading to difficulties in achieving consistent and dependable outcomes.

Conclusions

The experimental study and analysis were conducted on lightweight brick masonry walls reinforced with coconut rope netting, and the findings are presented in this research. Therefore, the following can be summarized:

- Lightweight brick masonry walls, when externally reinforced with coconut rope netting effectively improve the performance of the brick walls. The out-of-plane bending strength of the wall rises as the reinforcing ratio *(W_m)* of the coconut rope netting increases. The W_m increased from 4.10% to 5.50%. This led to a significant increase in the bending resistance of the walls, from 59.15% to 114.97%, when compared to the control samples.

- The findings demonstrate a positive correlation between ductility and reinforcement ratio implying that larger reinforcement ratios result in enhanced energy absorption by the test specimens.
- The maximum energy absorption and ductility values were 142 N-m and 3.79, respectively. The study results indicate that the energy absorption and ductility of the samples were increased by 30.61% and 87%, in comparison with the control samples, respectively.
- The cost-effectiveness of the reinforcement approach improves the ability of the wall to withstand out-of-plane bending strength. Furthermore, it increases the ductility and reduces the likelihood of failure compared to a wall without reinforcement.
- An analytical model was proposed to predict the maximum bending strength capability for the walls with reinforcement. The research findings suggest that the anticipated flexural strength of the reinforced specimens yielded lower estimations in comparison to the experimental results, with an average deviation of 0.4%, 3.3%, 0.24%, and 2.86% for patterns C1, C2, C3, and C4, respectively. The predicted ultimate bending strength capacity for the reinforced walls is deemed satisfactory.
- The limitation pertains to the difficulties involved in physically fabricating and affixing the coconut rope netting utilized for reinforcement. The manual creation of these components can result in discrepancies in their application, thereby affecting the consistency and efficacy of the reinforcement. The fluctuation can impact the performance of the walls, leading to difficulties in achieving consistent and dependable outcomes.
- Furthermore, this study is limited to the use of samples with only one diameter size and one layer of coconut netting, which may result in limited data. In the future study, it would be beneficial to vary the diameter size and the layers of coconut netting in each reinforcement pattern to obtain more diverse information.

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