

Research Article

Strengthening of Short Reinforced Concrete Columns by Using Natural Fiber Ropes as Confinement Composite Materials: Experimental Investigation

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ABSTRACT

It is widely known that concrete is one of the most used construction materials worldwide. However, strengthening or repair is an essential part of its lifecycle because it ages. The use of synthetic fiber-reinforced polymer (FRP) in strengthening RC structures has been proven to be effective. Recently, researchers have started investigating the use of natural FRPs (NFRPs) as an environmentally friendly alternative. However, the literature is still limited, and the efficiency of using different types of natural materials has not been confirmed, especially for concrete strength higher than 30 MPa. In the current study, three types of locally available NFRPs, including jute, cotton, and sisal, have been used to strengthen short-circular RC columns ($f'_c = 37.42$ MPa). Ten columns have been prepared, cast, and tested under monotonic axial loading until failure. The effects of the number of confinement layers (1, 2, and 4 layers) have also been investigated. The results show that NFRPs can significantly improve the axial strength of short RC columns. Sisal NFRPs provided the greatest enhancement in axial strength (83%), followed by jute (43%) and cotton (35%). In general, increasing the number of confinement layers increases the axial strength of RC columns. However, more confinement did not show a clear pattern on the deformation performance.

1. INTRODUCTION

Reinforced concrete is one of the most widely used and preferred construction materials in the building sector due to its strength and durability. Consequently, it is extensively used in a wide range of infrastructure and civil engineering applications [1–3]. However, as reinforced concrete structures age over their service life, they sustain damage as a result of many reasons such as inadequate reinforcement, steel corrosion [4–7], fatigue failure [8,9], unexpected heavy loads [10,11] and severe environments [12,13]. Damage includes concrete fracture, cracking, spalling, surface separation that exposes the reinforcing steel to the weather, corrosion of steel reinforcement, and a reduction in concrete strength. These types of damage can weaken structural stability and lead to increased repair and maintenance costs [14,15]. Thus, it is essential to seek an economically feasible technique and new materials to repair and strengthen concrete building [16,17]. Fiber-reinforced polymers (FRPs) have appeared as preferred strengthening materials because of their valuable properties such as high tensile strength, ability to resist corrosion, and relatively easy installation [18,19]. They contribute significantly in enhancing the strength capacity and ductility of concrete structures without adding considerable weight [20,21]. In recent years, major concern has been raised to global warming, especially CO₂ emissions. Artificial Fiber Reinforced Polymers (FRPs) are expensive materials and have a large carbon footprint [22–26]. They are produced from non-renewable fossil resources, and their production requires a large amount of energy while releasing harmful gases into the atmosphere, resulting in considerable environmental impacts [27].

Therefore, natural fibers have appeared as an alternative to artificial fibers. Nowadays, natural fiber-reinforced polymers (NFRPs) are achieving a performance comparable to synthetic FRP materials because of their desirable mechanical properties and low environmental effects. Despite showing potential as strengthening materials for concrete structures, research on their application remains limited compared with that on synthetic fibers [28,29]. Among the various properties

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of natural fibers, their ductile behavior has attracted significant attention because of its potential to enhance the structural performance of concrete members. Natural materials are considered ductile because they undergo large deformation before fracture and they have the ability to absorb energy through elongation. They often show high durability and can endure high strains and stresses efficiently. Therefore, natural materials, such as cotton, jute, hemp, flax, and sisal ropes and textiles represent a significant replacement to improve concrete strength and ductility [30–33]. The use of NFRPs is increasing, particularly in construction, and they are expected to control the market for NFRPs due to their eco-friendly properties. Despite their growing use, further research is required to enhance their mechanical performance and to address issues such as thermal stability, moisture absorption, quality of fibers, incompatibility with polymer materials and resistance to extreme weather conditions [34,35].

Comparative investigations have revealed that bio-based fiber composites, including jute, flax, cotton, and sisal materials, usually exhibit lower confinement efficiency than carbon FRP (CFRP) or basalt FRP (BFRP) under identical confinement configurations. This behavior occurs primarily because natural NFRPs have lower elastic modulus and tensile strength. However, they can still provide considerable improvements in ductility and strength while reducing material cost and environmental impact. They can improve the properties of brittle materials, such as concrete, by serving as an effective confinement [36,37]. In many studies, NFRPs have been used in reinforced concrete columns to enhance confinements. For example, Hussain et. al [38] found that hemp can provide better confinement than cotton FRPs. For instance, hemp confinements achieved more than two hundred percent in compressive strength and two hundred seventy percent in strain for circular cross sections. This was not the case with square and rectangular sections in which stress concentration occurred at the corners and reduced the strength. To improve the strength of square concrete specimens, confinements with NFRPs were employed by changing the corner radius, showing a relationship between the size of the corner radius and the improvement in strength [39]. Moreover, research has shown that the efficiency of NFRP confinement was comparable to that of glass fiber- and carbon fiber-reinforced composites [40–43].

To further improve structural performance while reducing the brittleness associated with synthetic FRP systems, hybrid confinement techniques have been developed by combining natural materials with large rupture strains and FRP materials with high tensile strength. This combination enhances energy dissipation and ductility while reducing the risk of sudden failure [44]. Hybrid confinement has also been successfully applied to improve the compressive, shear, and flexural performance of concrete structures [45]. The results of the previous studies demonstrated significant improvements in compressive strength, ultimate strain, and energy dissipation, particularly for circular specimens [46]. Although hybrid systems have shown promise as strengthening solutions, research on combining synthetic FRPs with natural fibers remains limited. Recent studies highlighted the need for further exploration of optimal FRP thickness, layering, and material compatibility in hybrid compositions [47]. In addition, previous research has indicated that the confinement effectiveness decreased as the compressive strength of the unconfined concrete increased [48,49]. As of today, and to the best of the authors' knowledge, there are only five studies [37,50–53] have investigated the use of NFRPs in confinement of RC columns the compressive strength of which was higher than 30 MPa. Three of them [37,50,52] used plain concrete columns without longitudinal reinforcement. The other two [51,53] investigated hybrid composite sheets rather than NFRPs. As a result, research on the use of natural fibers in strengthening RC columns with compressive strength higher than 30 MPa is almost not available.

Therefore, in the current study, three types of natural fibers, selected based on their common use and local availability, were experimentally investigated for strengthening short RC columns made with 37.42-MPa concrete. Jute, cotton, and sisal ropes were used as NFRPs for strengthening nine specimens, and their performance was compared to a typical short and circular RC column. The stress-strain relationships, ductility, and failure modes were evaluated experimentally and discussed in the current study.

2. EXPERIMENTAL PROGRAM

The experimental program consisted of preparing, casting, strengthening, and testing ten circular reinforced concrete (RC) columns. All the tested specimens had the same dimensions; 150 mm in diameter and 300 mm in height, and the same reinforcement details. In this study, the effects of additional confinement with three types of natural ropes, including jute, cotton, and sisal, on short RC specimens were investigated. One-, two-, and four-layers of natural ropes impregnated with epoxy were applied to confine the specimens. Table 1 shows the details of the specimens and the summary of the experimental results. For each specimen, the nomenclature was chosen based on the confinement materials used for strengthening and the number of confinement layers. The first letter, J, C, and S, refers to the natural material used in strengthening (jute, cotton, and sisal, respectively). Moreover, in all specimens, the letter H represents the compressive strength used in this study (designed strength of 40 MPa) that is higher than the other groups; as the specimens used in the current study are part of a larger experimental investigation considering other compressive strengths. Finally, the number at the end of the label indicates the number of natural FRP (NFRP) layers. For example, the symbol C-H-4 represents a

reinforced concrete specimen strengthened with 4 layers of cotton ropes. In addition, the control specimen, which represents a typical short RC column, is labeled as CTR-H. Finally, it must be stated that only one specimen was tested per configuration ($n = 1$), and this is one of the limitations of the current study.

TABLE I. DETAILS OF SPECIMENS AND SUMMARY OF EXPERIMENTAL RESULTS

Specimen name	Strengthening material	Number of layers	Maximum axial stress, MPa	Improvement in axial strength	Axial strain at max. stress	Axial strain at 20% strength decay ^b	Maximum axial strain	Lateral strain at max. axial stress	Max. lateral strain
CTR-H	None	None	39.70	N/A	0.0032	0.0123	0.0140	0.0016	0.0129
J-H-1	Jute fiber	1	48.06	21%	0.0073	0.0100	0.0155	0.0031	0.0072
J-H-2		2	48.45	22%	0.0048	0.0096	0.0112	0.0044	0.0123
J-H-4		4	56.87	43%	0.0044	0.0079	0.0086	0.0048 ^a	0.0048
C-H-1	Cotton fiber	1	45.23	14%	0.0041	0.0086	0.0103	0.0112	0.0147
C-H-2		2	52.94	33%	0.0051	0.0084	0.0124	0.0034	0.0072
C-H-4		4	53.79	35%	0.0074	N/A	0.0132	0.0023	0.0077
S-H-1	Sisal fiber	1	56.38	42%	0.0097	N/A	0.0107	0.0078	0.0080
S-H-2		2	60.89	53%	0.0067	0.0144	0.0186	0.0062	0.0076
S-H-4		4	72.66	83%	0.0113	N/A	0.0127	0.0014	0.0015

^a The data-logger readings for lateral strain was lost during the test and became constant at 0.0048.

^b When the axial strain at 20% strength decay is not available, the maximum axial strain was used for ductility measurements discussed in section 3.2.

2.1 Materials Properties

2.1.1 Concrete

The concrete mix used in this study consisted of ordinary Portland cement, river sand with a fineness modulus of 2.72, crushed aggregate with a maximum size of 12.5 mm, and tap water. The concrete mixture was designed to produce a concrete compressive strength of 40 MPa at 28 days. All specimens were cast from the same concrete mixture. The mix proportions of cement, water, fine aggregate, and coarse aggregate were 500, 185, 680, 1000 kg per cubic meter, respectively. The water-to-cement ratio was 0.37. After 24 hours of casting, the specimens were demolded and immersed in water for 28 days for curing. Three plain concrete cylinders were tested at the age of 28 days and the average compressive strength was 37.42 MPa, with a standard deviation of 0.731 MPa. The average compressive strength was 6.45% lower than the target compressive strength (40 MPa). However, slight difference between the target and the obtained strengths is probably related to the uncertainty in the process of mixing, compacting, curing, or the differences in moisture content of the aggregate. For the purpose of this study, the average compressive strength obtained from experimentally testing three cylinders (37.42 MPa) was taken as the concrete compressive strength of all specimens.

2.1.2 Steel Reinforcement

For all specimens, four 10-mm rebars were used for longitudinal reinforcement with a reinforcement ratio of 0.0178. According to the datasheet from the manufacturer, the specified yield strength and the ultimate tensile strength for the 10-mm steel rebar were 480 MPa and 600 MPa, respectively. Moreover, 6-mm smooth bars with a specified yield strength of 320 MPa and ultimate strength of 500 MPa were used as ties. The spacing between the ties was 120 mm. Figure 1 illustrates the configuration, dimensions, and reinforcement details for all the specimens.

2.1.3 NFRP composites

In this study, three types of locally available natural ropes, including jute, cotton, and sisal, were impregnated with epoxy (Sikadur-330) to produce a composite rope used to confine the reinforced concrete columns. It should be mentioned that the high viscosity of Sikadur-330 may limit epoxy penetration into the natural fibers. However, Sikadur-330 was chosen due to its high bond strength with concrete, which is critical for effective confinement. In addition, Sikadur-330 is locally available, and has previously been used successfully with jute ropes in confinement strengthening of RC columns [54,55]. Based on the manufacturer's data sheet, the tensile strength, tensile modulus of elasticity, tensile strain at break are 30 MPa, 4500 MPa, and 0.9%, respectively. Figure 2 shows actual photos of the three types of natural ropes used in the current study. Since single round twisted ropes were used for confinement in the current study; not a flat unidirectional sheet, the mechanical properties of single composite ropes were examined. The tensile strength of the composite natural rope impregnated with epoxy was evaluated according to ASTM A931-18 [56] which was adopted by Hussain et. al. [30].

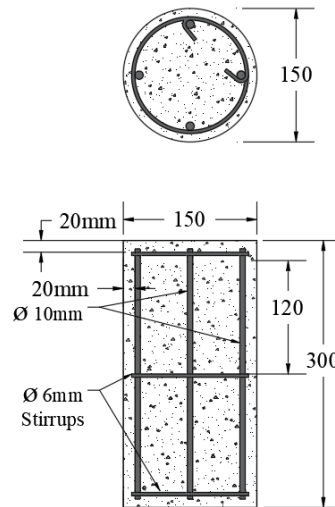


Fig. 1. Configuration, dimensions, and reinforcement details of the tested specimens.

Using a universal tensile testing machine with a 50 kN capacity and a displacement control rate of 1.5 mm/min, five composite specimens from each rope type were tested to evaluate the tensile strength of the natural fiber reinforced polymers (NFRPs). The specimens were prepared by cutting the dry rope into 300 mm lengths and impregnating them with epoxy. Two pieces of aluminum were glued to the ends of the specimens to prevent damage at the tips of the ropes during the test caused by gripping system of the testing machine. The testing setup of the NFRP is shown in Figure 3. Table 2 presents the experimental results of the tensile strength for each NFRP specimen described above, in addition to average diameters, equivalent thickness, tensile strength for each NFRP specimen, average tensile strength, standard deviation, coefficient of variance, average elastic modulus, and average rupture strain for all fifteen specimens. The equivalent thickness was determined based on the following equation; $t_{eq} = A_{eff}/s$; where the t_{eq} is the equivalent thickness, A_{eff} is the effective area, determined from the effective diameter of the rope cross section, and s is the center-to-center spacing between single ropes. The effective diameters, listed in Table 2, were determined from the density and the unit weight of natural ropes by determining the solid volume of the fibers in one meter. The solid volume of the natural fiber in one meter was determined by dividing the unit weight by the density (Table 2).

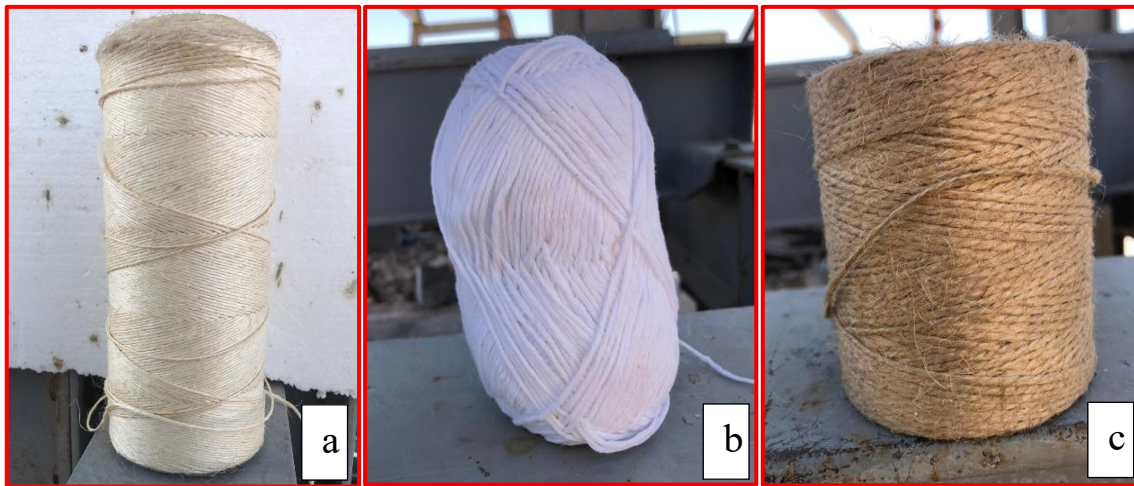


Fig. 2. Natural Ropes (a) Sisal (b) Cotton, (c) Jute

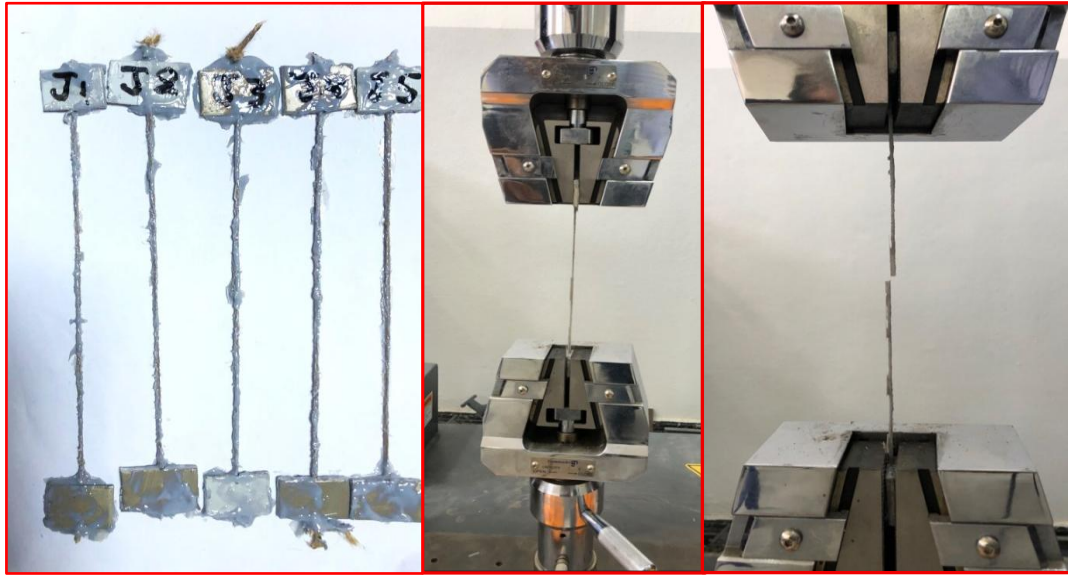


Fig. 3. Tensile test of the composite natural ropes (NFRPs)

TABLE II. TENSILE TEST RESULTS FOR COMPOSITE NATURAL ROPES

Type of natural rope	Average nominal diameter, mm	Density of the natural ropes (g/cm ³)	Unit weight (g/m)	The average effective diameter (mm)	Equivalent area per layer (mm ²)	Equivalent thickness (mm)	Tensile strength (MPa)	Average tensile strength (MPa)	Standard deviation (MPa)	Coefficient of variation (%)	Average elastic modulus (GPa)	Average rupture strain (%)
Jute	J1	1.6	1.38	1.67	1.24	226	91.49	113.78	27.82	24.45	16.24	1.5
	J2						85.95					
	J3						138.32					
	J4						147.74					
	J5						105.43					
Cotton	C1	1.4	1.52	1.4	1.09	198	60.23	59.37	2.88	4.85	7.65	1.1
	C2						60.13					
	C3						63.16					
	C4						55.47					
	C5						57.84					
Sisal	S1	1.5	1.46	1.55	1.16	212	172.35	195.21	25.58	13.11	22.82	1.9
	S2						189.68					
	S3						191.65					
	S4						183.42					
	S5						238.95					

2.2 Confinement

With regards to steel reinforcement, all specimens are confined with steel ties as explained in section 2.1.2. Therefore, the terminology of unconfined concrete is not applicable in the current study. In addition, for laboratory testing purposes, a 20-mm wide CFRP sheet was used at the tips of all columns (top and bottom) as an additional confinement to prevent stress concentration and concrete spalling causing premature failure. A unidirectional CFRP sheet with a thickness of 0.167 mm, ultimate tensile strength of 3123 MPa, and ultimate tensile strain of 1.34%, as experimentally determined by Aules et al [57], was used in the current study.



Fig. 4. Adding CFRP strips to both ends of the columns



Fig. 5. Steps for applying natural ropes on RC columns for confinement

Except for the control specimen (CTR-H), all other specimens were confined with one, two, or four layers of natural fiber reinforced polymer (NFRP). After 28 days of curing, the specimens were prepared for confinement. The first step was cleaning the surface of dust and loose particles using a grinding tool and air pressure. Then, as mentioned earlier, the 20-mm CFRP sheets at the column tips were applied, as shown in Figure 4. After that, a thick layer of Sikadur-330 epoxy was applied to the concrete surface with a brush to the cleaned concrete surface (Figure 5a, b). The dry rope was then tied (fixed) at one of the column's ends by forming a tied knot and wrapped around the column (Figure 5c, d). During the

wrapping process, the rope was tied closely without noticeable spacing between ropes (Figure 5e). Therefore, the value of the winding pitches was equal to the diameter of the natural rope. Regarding winding tension applied during the confinement process, the rope was hand-tied, unmeasured. To achieve a high level of epoxy penetration, a rubber roller was used to press the epoxy through the fibers to ensure sufficient epoxy-fiber saturation. After completing the application of one layer, a layer of epoxy was added on top of the first layer, using a brush, to ensure that the natural fibers are fully saturated with the epoxy (Figure 5f). More layers were added using the same procedure and after the underlay layer was dry (Figure 5g, h).

2.3 Test setup and instrumentations

All the specimens were tested under axial load up to failure. A universal testing machine with a capacity of 200 Tons was used to apply a monotonic axial load. A loading rate of 4kN/s was adopted in the current study [58]. Unfortunately, a displacement-control testing machine was not available in the laboratory. Therefore, when the load reached approximately 80% of the expected peak load, the lab technician would control the hydraulic pressure applied to the loading frame, carefully trying to reach the maximum and then kept the load constant while specimens were deforming. A monitor-screen was used to present the immediate data from the load cell and the LVDTs in front of the technician and the testing team. The load was measured using a strain-gauge-type load cell with a maximum capacity of 300 Tons. For displacement measurements, two Linear Variable Differential Transformers (LVDTs) on both sides of the specimens were implemented to determine the axial displacement. In addition, a circumferential expansion (dilation) of the column was quantified using a steel ring equipped with a (LVDT), enabling calculation of the equivalent hoop strain. The hoop strain (lateral strain) was calculated by dividing the displacements measured by the lateral LVDT (mm) by the circumference of the column (mm). All the sensors (load cell and LVDTs) were connected to a data-logging system that provided 10 data points to the computer per second. Figure 6 shows the instrumentations and the test setup used in the current study.

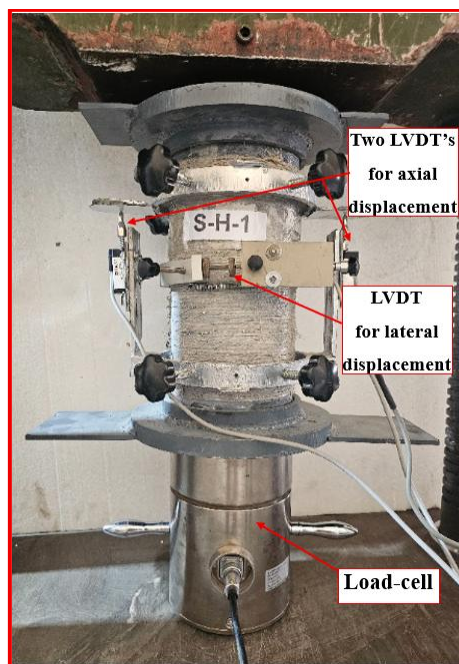


Fig. 6. Instrumentation and loading setup

3. RESULTS AND DISCUSSIONS

This section presents and discusses the results of experimentally testing ten short reinforced concrete (RC) columns under axial loading. The discussion focuses on the compressive stress-strain behavior of the RC columns, the failure modes, and the ductility of the specimens. The behavior of the RC columns confined with natural ropes are compared with the control specimen (CTR-H). It must be noted that every reported value is a single observation as no replication of specimens was used in the current study ($n = 1$).

3.1 Stress-strain behavior

Figure 7 shows the axial stress-strain curves for ten specimens compared based on the natural material (jute, cotton, and sisal) used to confine (strengthen) the RC columns. As expected, it was observed that the initial slope of the stress-strain curves was linear and almost the same for all specimens. The small fluctuations observed in the linear portion of the stress-strain curves of specimens S-H-1 and C-H-4 (Figures 7a and 7c) are likely attributed to measurement noise and variations in data-acquisition system. Overall, all strengthened specimens behaved similar to the control specimen (CTR-H) in the linear part of the stress-strain curve. However, except for J-H-1 and S-H-1, confined columns showed higher stiffness before reaching the maximum axial strength of the control specimen (39.70 MPa). Regarding the initial stiffness of J-H-1 and S-H-1, the initial stiffnesses of both specimens were almost identical. However, as it can be seen in Figure 7 (a), the stress-strain curve of J-H-1 experienced lower stiffness beyond the point where the axial stress reached 23.77 MPa. Overall, after the maximum axial strength achieved by the control specimen (CTR-H), the stress-strain curves continued in softer stiffness than the linear part but in ascending pattern until the maximum strength was achieved. Afterward, the stresses were decreased gradually while axial strain increased until the failure for specimens with one or two layers of NFRP ropes. For specimens with four layers of NFRP ropes, the failure was more brittle as the stress continued to increase and failed suddenly without previous notice.

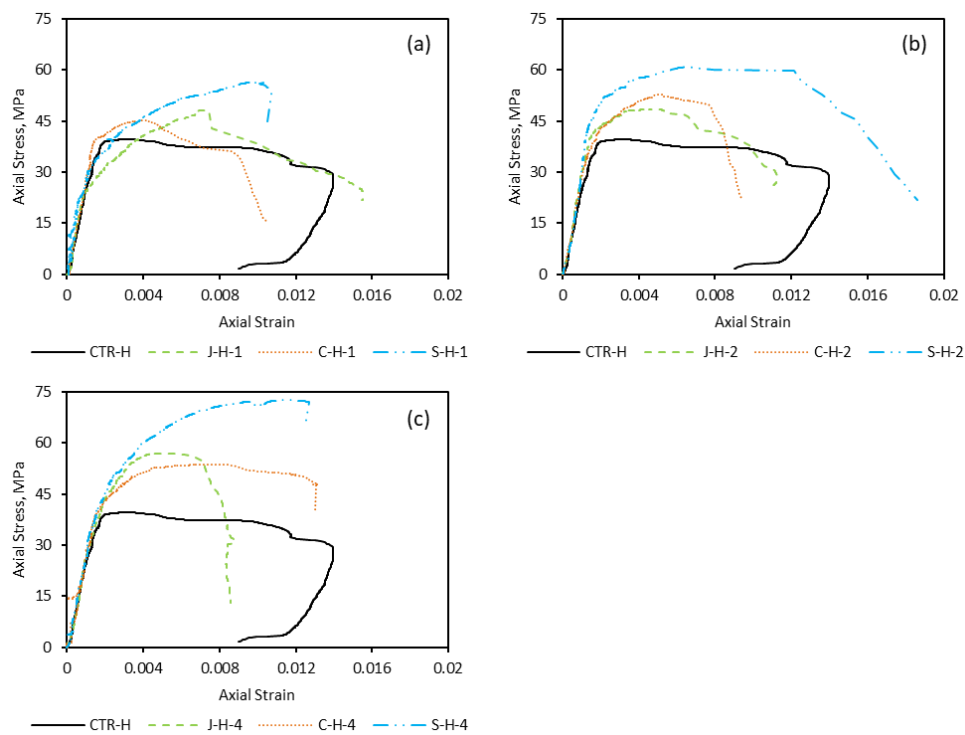


Fig. 7. Experimental results showing the stress-strain curves of the tested columns; (a) one layer, (b) two layers, and (c) three layers of NFRP

It can be seen that specimens confined with sisal ropes always achieved the highest strength no matter how many layers of ropes were used. This is mainly due to the fact that the tensile strength and the modulus of elasticity of sisal ropes are the highest among the three types of natural ropes used in the current study (Table 2). On the other hand, comparing jute with cotton ropes, specimens confined with jute ropes also achieved slightly higher strength compared to specimens confined with cotton ropes, except for specimen C-H-2 as the ultimate strength was slightly higher than that of J-H-2. Variations in specimen preparation, possible minor inconsistencies in testing, mixing, confinement process, in addition to material heterogeneity could be attributed to this slight deviation in the result of one specimen. This uncertainty would have been verified if more than one specimen were tested per each configuration. Therefore, more tests are required to verify the results reported in the current study.

Overall, specimens with sisal FRP had the highest compressive strength and the highest axial strain associated with the maximum stress. This indicates that sisal ropes could provide the maximum confinement stress needed for the short RC columns. However, the expanding of the columns in the lateral (hoop) direction was less when more confinement (more layers of NFRP) was provided as it can be seen from the maximum achieved lateral strain in Table 1. This was true for all specimens except specimen J-H-2 and C-H-2. The observation of reducing the maximum lateral strain when more

confinement is provided could be attributed to the increase in lateral stiffness when more layers of NFRP confinement is provided, which then increases the resistance to concrete dilation. Saleem et. al [59] found that lateral deformation depends not only on confinement stiffness but also on the cross-sectional shape and properties of materials for FRP-confined RC columns. In addition, it has been reported that increasing the confinement stiffness decreases the maximum achieved Poisson's ratio [60]. However, the reduction in maximum lateral strain of RC columns observed in the current study as a result of increasing the confinement stiffness should be considered as an experimental observation limited to the parameters of the current study rather than a universal observation. Moreover, the values of lateral strain corresponding to the maximum axial stress decreased with the increase of confinement stiffness (i.e. number of NFRP layers) for cotton- and sisal-confined specimens. On the other hand, the values of lateral strain corresponding to the maximum axial stress increased with the increase of confinement stiffness for columns confined with jute FRPs. The observation for cotton- and sisal-confined specimens can be explained by the fact that additional confinement leads to higher stiffness and higher resistance to concrete expansion in lateral direction (lateral strain) [61–63]. However, jute-confined specimens showed the opposite behavior as the values of lateral strain corresponding to the maximum axial stress increased with the increase of number of NFRP layers. Therefore, more tests are required to verify the results of the current study regarding the hoop strain behavior of NFRP-confined RC columns.

Table 1 presents and compares the experimental results of all tested specimens. It shows that the improvement in axial strength of RC columns ranged from 14% (C-H-1) to 83% (S-H-4). All strengthened specimens achieved higher compressive strength than the control specimen, which indicates that NFRP can be used to improve the compressive strength of short RC columns. This observation is aligned with research findings from previous studies [30,38,41,64]. Another observation was that increasing the number of NFRP layers always increased the axial strength of the specimens. However, the improvement was not consistent between the materials. For example, the compressive strength for specimens with one, two, and four layers of jute ropes improved by 21%, 22%, and 43%, respectively. On the other hand, the compressive strength for specimens with one, two, and four layers of cotton ropes improved by 14%, 33%, and 35%, respectively. The improvement was more consistent for specimens with sisal ropes as it can be seen in Table 1. It is worth mentioning that confinement with only one layer of sisal rope was more efficient than 4 layers of cotton ropes and almost the same as 4 layers of jute ropes.

Finally, it should be mentioned that the portion of the stress-strain curve of the control specimen (CTR-H) where the axial strain started to decrease can be considered as unreliable measurements of the strain. This portion represents the moment of failure where the axial stress was returning to the zero value. When the pressure of the hydraulic ram, which is responsible of applying the axial load, decreases significantly due to the loss in column's resistance to axial force, the pressure that was applied to the remaining parts of the crushed column, including the buckled longitudinal steel reinforcements, was reduced. Therefore, the LVDTs either slipped or recorded less displacements during this release of applied force. This portion can be removed from Figure 7 as it represents an unreliable behavior, but the authors wanted to report all the recorded measurements until the test stopped. It should be mentioned that the strain corresponding to 20% decay in axial strength, which will later be used for ductility measurements, was recorded before this phenomenon.

3.2 Ductility

To have a sense of ductility, deformability or the deformation capacity from the measured axial stress-strain curves, and because the yield strain was not measured in this study, the ductility presented in Figure 8 was measured by dividing the maximum achieved axial strain (for specimens with sudden-brittle failure) or the ultimate strain recorded at 20% drop in load capacity (for specimens with gradual post-peak softening) by the strain at which the slope of the stress-strain curve of the control specimen (CTR-H) changed significantly. At this point, the axial strain of the control specimen (CTR-H) started to increase while the axial stress remained almost constant. In the current study, the strain at this point was equal to 0.0019. This is consistent with standard research literature and international codes as it is internationally accepted to assume a theoretical value of 0.002 as the base strain for ductility measurements [65–67]. In the current study, a strain value of 0.002 was used to calculate the ductility index presented in Figure 8. In addition, assuming the ultimate strain as the strain corresponding to 20% drop in strength is widely accepted [68–71].

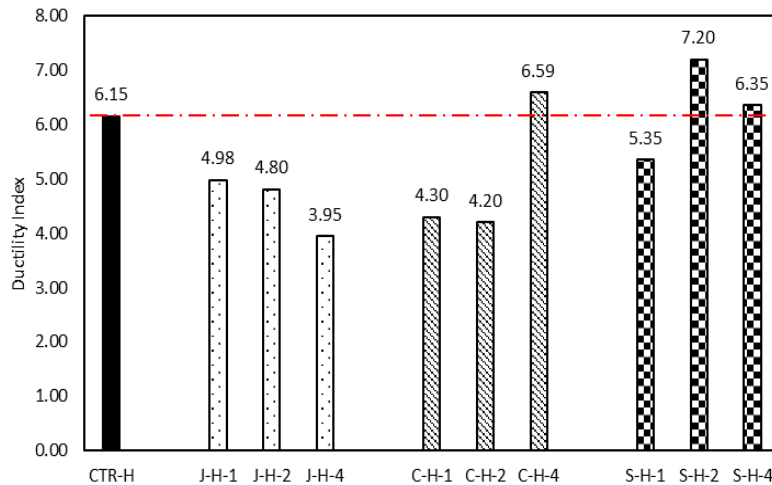


Fig. 8. Ductility Index based on experimental results

Based on the results of the current study, there was no clear pattern observed on the effects of confinement level on the ductility. As shown in Figure 8, the ductility of specimens confined with jute decreased with increasing the confinement from one layer to four. However, the ductility of specimens confined with cotton ropes increased significantly when four cotton ropes were used (C-H-4). From Figure 7 and Table 1, it can be observed that the performance of specimen C-H-4 was unique as the column continued to deform while the axial load was almost constant until it achieved very high deformability (axial strain) before failure. C-H-4 also achieved a high value of lateral deformation (0.0077). On the other hand, specimens confined with two layers of sisal ropes achieved the highest ductility compared with all other specimens because the failure pattern was gradual and the strain corresponding to 20% drop in strength was the highest among all other specimens. Figure 8 shows that only three specimens (C-H-4, S-H-2, and S-H-4) achieved higher ductility index than that of the control specimen. This observation confirms that the use of sisal ropes in lateral confinement of short RC columns is more effective not only in terms of strength improvement but also in ductility or deformability.

Overall, the results of the current study were not aligned with the findings of previous studies which showed that increasing confinement level increased the ductility of RC columns [38,72,73]. However, most of the previous studies that showed the ductility increased with the increase of confinement were based on testing plain concrete. In conclusion, more tests are required to verify the observed discrepancies in the ductility results of the current study.

3.3 Effects of confinement amount (number of layers)

Figure 9 shows that strengthening RC columns with one and two layers of Jute ropes had almost the same improvement of axial strength. However, the strength improvement was more significant when using four layers of jute. On the other hand, the strength improvement for C-H-2 was clear compared to C-H-1. However, using four layers of cotton did not have significant improvement in terms of strength compared to the specimen with two layers of cotton ropes (2% of strength improvement). The benefit of four layers of cotton was clear in terms of the axial strain associated with the maximum strength (Figure 7). As a result, confining RC columns with four layers of cotton ropes allowed the specimen to withstand larger deformation before failure. The maximum lateral strain for C-H-4 was also slightly higher than that of C-H-2 (Table 1). Overall, it was expected to have a higher axial strength for specimen C-H-4 compared to C-H-2 because two additional confinement layers were added. However, it seemed that the two additional layers of cotton NFRPs helped only in terms of keeping the column deform with an almost constant axial load, leading to a much higher ductility. In addition, the only 2% of improvement in strength when comparing C-H-4 to C-H-2 could be attributed to the much lower stiffness of cotton ropes compared to jute and sisal ropes [74,75]. Low stiffness allowed the column to have larger deformation and failed to handle more axial forces. Moreover, since only one specimen was tested, more tests are required to confirm this observation. Finally, it should be mentioned that concrete is a nonhomogeneous material, and discrepancies in results could also be attributed to human errors and inconsistencies in casting, curing, and testing.

The effects of number of confinement layers were clearer for RC columns confined with sisal ropes. The improvement in strength when changing the confinement from one layer to two and four can clearly be seen. Specimens S-H-1 and S-H-4 failed suddenly after achieving the maximum strength. However, the failure for specimen S-H-2 was gradual and smooth after reaching the maximum strength, which allowed specimen S-H-2 to achieve the highest ductility. It can be observed from Figure 9 that increasing the number of layers increases the axial strength of short RC columns.

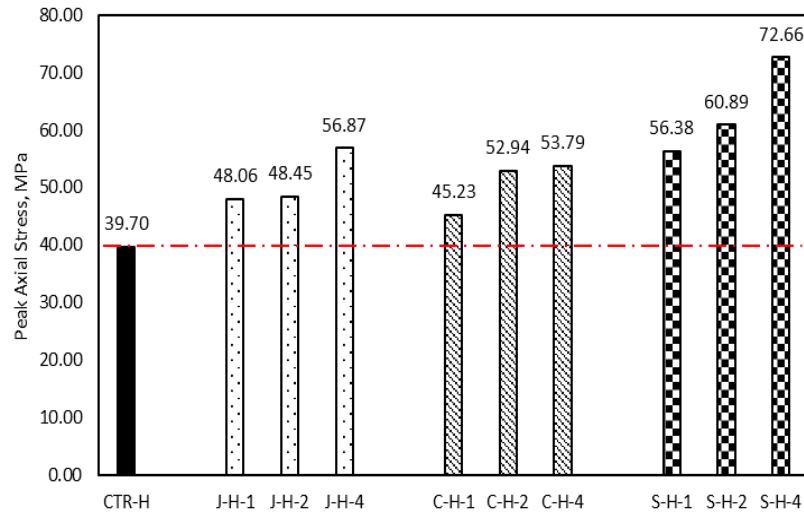


Fig. 9. Achieved ultimate compressive strength compared to the control specimen

3.4 Failure modes

The ultimate failure modes of all specimens tested in the current study are presented in Figure 10. As mentioned before, the top and bottom 20 mm of all tested columns were wrapped with one layer of CFRP sheet just to avoid premature failure due to stress concentration at the tips of the columns. The failure mode for the control specimen (CTR-H) exhibited delamination of concrete cover and spalling. In addition, slightly before achieving the ultimate strength, CFRP slippage at the overlapping zone and then CFRP rupture was observed at the top of the column followed by concrete cover delamination at the same location. Sufficient overlap of 150 mm of CFRP confinement was applied [76]. However, the slippage of CFRP sheet that occurred in fractions of a second before the failure was most likely due to the delamination and cracks developed at the surrounding concrete. It should be noted that the axial strength achieved by the control specimen (39.70 MPa) was almost similar to the expected nominal strength ($P_0 = 39.77$ MPa) considering the equation proposed by ACI 318-25 [77]. Therefore, it can be stated that the control specimen reached its ultimate strength, and the slippage or rupture of CFRP did not have a significant effect on the results.

For specimens confined with one layer of NFRP (J-H-1, C-H-1, and S-H-1), the failure started around the middle of the column and continued to progress until rupture of NFRP occurred indicating not a sufficient confinement to prevent the buckling of the longitudinal reinforcing rebars. Although specimen C-H-1 exhibited similar failure mode in the beginning (concentrated mainly at the middle), the failure progressed along a wider height of the column compared with specimens confined with one layer of jute and sisal ropes. The observed failure modes for the control specimen and specimens confined with one layer of natural fibers are aligned with the finding of previous studies [38,47,72].

A failure mode of NFRP rupture was also observed for specimens confined with two and four layers of natural fiber ropes. However, the rupture was along almost the full length of the columns indicating an improvement in stress distribution mainly because of the stronger confinement. This was not true for specimen S-H-2 as the rupture of the NFRP distributed from the mid-height to the top of the columns and not along the entire height. The observed failure mode for S-H-2 could be due to the fact that S-H-2 was able to withstand a very high strength (higher than specimens with 4 layers of jute and cotton ropes) and needed a larger amount of confinement for such a high load. Overall, it can be stated that small amount of confinement (i.e. one layer) provided a failure mode with stress concentration at or near the middle of the columns (Figure 10), and the failure type was most likely gradual post-peak softening until collapse (Figure 7). However, for higher level of confinement (i.e. four layers), the stress evenly distributed, the NFRP rupture occurred along the entire height of the columns, and the failure was more likely to be sudden and explosive. This observation is aligned with the previous literature [38,47,72,73].



Fig. 10. Failure modes for all tested specimens

4. CONCLUSIONS

A total of ten RC columns, including one reference typical RC column and nine RC columns confined with NFRPs have been experimentally tested to investigate the use of NFRPs in strengthening short RC columns. Jute, cotton, and sisal natural ropes were used in the current study as they are the most locally available natural fibers and previously proven to be a potential alternative to synthetic FRPs. All specimens have been tested under monotonic axial loading, and the following conclusions can be drawn based on the experimental results of the current study:

1. The positive effects on axial strength of RC columns strengthened with NFRPs have been declared by previous studies. However, most of the findings were limited to testing low-strength RC columns. In the current study, it was found that strengthening short RC columns with NFRPs confinement, including jute, cotton, and sisal could enhance the axial compressive strength significantly. The improvement in compressive strength ranged from 14% (C-H-1) to 83% (S-H-4).
2. Among the three types of natural fibers, strengthening short RC columns with sisal ropes achieved the highest compressive strength. Specimens strengthened with only one layer of sisal ropes achieved higher compressive strength compared with four layers of cotton ropes and achieved almost similar compressive strength to that with four layers of jute ropes.
3. As expected, increasing the number of layers of NFRPs increases the compressive strength of short RC columns. The gain in strength was significant, and the pattern was clear for sisal-confined columns. However, the gain in strength was insignificant in some cases (C-H-4 compared to C-H-2; and J-H-1 compared to J-H-2). Therefore, the marginal benefit of additional NFRP layers of confinements depends strongly on the fiber type.
4. No clear pattern was observed in terms of the effects of NFRP confinement on the ductility or deformability of RC columns. In some specimens, increasing the confinement increased the strength but decreased the ductility. On the other hand, the deformability was increased with the increase of the level of confinement. From the limited tests provided in the current study, only three specimens (C-H-4, S-H-2, and S-H-4) achieved higher ductility index than the control specimen.
5. Specimens with low level of confinement (i.e. one layer of NFRPs) tends to fail due to fiber rupture concentrated around the mid-height of the columns. On the other hand, increasing the level of confinement (increasing the number of layers to two or four) helped to distribute the stress along the entire height of the column. Therefore, specimens with two or four layers were able to withstand higher loads, and the failure mode was rupture of NFRPs almost along the entire height of the column.
6. More tests are required to verify the observations reported in this study due to the limited tests that were conducted on short RC columns, and due to the fact that only one specimen was tested per each configuration. Other limitations of the current study like larger-scale specimens, higher concrete strengths, cyclic loading, and additional types of NFRPs may be considered in the future studies.

CRediT Author Contributions

Yasir M. Saeed: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Wisam A. Aules:** Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft. **Hosam A. Al-Azzawi:** Investigation, Resources, Writing - original draft. **Tara R. AbdulWahab:** Resources, Writing - original draft. **Franz N. Rad:** Conceptualization, Supervision, Validation, Writing - review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Ethical Approval

This study did not involve human or animal subjects, and ethical approval was not required.

Data Availability Statement

Available from the corresponding author upon reasonable request.

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