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# Natural fiber-based partially and spiral confinement: A sustainable solution for improving reinforced concrete column performance

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## ABSTRACT

The use of abaca-fiber as an alternative material in natural fiber-reinforced polymer composites (NFPCs) reinforcement for concrete columns offers not only technical advantages in terms of strength and production energy efficiency, but also presents a sustainable bio-material-based solution. This study aims, to evaluate the structural performance of cylindrical reinforced concrete (RC) columns externally confined using NFPCs sheets made from abaca-fibers. Two confinement techniques were applied: spiral and partial wrapping. The test specimens measured 205 mm (in-diameter) x 615 mm (in-height) and were reinforced internally with six longitudinal (10 mm diameter) and transverse steel bars (8 mm diameter) reinforcement. One specimen was strengthened using a confinement spiral wrapping of NFPCs (CS-NFPCs), while another employed partial confinement (CP-NFPCs). Axial compressive tests under monotonic loading were performed, and compared to an unconfined control specimen normal confinement (NC). The spiral NFRP confinement improved the axial load capacity by 22.68% and significantly enhanced ductility by 347%. In contrast, partial wrapping resulted in a 13.79% increase in axial capacity and a 50% improvement in ductility. These findings demonstrate the effectiveness of abaca-fiber based NFPC as a sustainable alternative for enhancing both strength and ductility in RC columns.

**Keywords:** reinforced concrete columns, NFPCs, abaca-fiber, axial load capacity, ductility enhancement.

## INTRODUCTION

Reinforced concrete (RC) structures worldwide continue to face safety and performance challenges due to natural disasters (e.g., earthquakes), structural aging, suboptimal initial design, exposure to harsh environmental conditions, and insufficient maintenance practices [1–4]. To address these challenges and extend the functional lifespan of aging infrastructure, the retrofitting (the change procedure of existing structures) and strengthening of RC members have become a critical area of focus within structural engineering [5–7]. Several strengthening methods, fiber-reinforced polymer (FRP) composites have attracted considerable interest owing to their exceptional strength to weight-ratio, corrosion-resistance, ease of installation, and demonstrated effectiveness in enhancing the load-bearing capacity and ductility of RC elements [8,9]. Despite these advantages, conventional FRP composites are typically manufactured from synthetic-fibers: carbon, glass, or aramid, which are energy-intensive to produce, expensive, and raise concerns related to long-term environmental sustainability.

In light of the environmental and economic limitations of synthetic FRPs, the development of NFPCs composites has appeared as a sustainable and promising alternative-material [10]. These materials utilize renewable plant-based fibers, such as jute, flax, hemp, and abaca as reinforcing agents within polymer matrices, thereby reducing the ecological footprint and cost associated with traditional FRPs [11]. Natural fibers are biodegradable, abundantly available, and offer acceptable mechanical properties, particularly in applications where high stiffness and moderate strength are required [10, 12]. Among these, abaca-fiber (Musa textilis), a bast fiber native to the Philippines and widely cultivated in Southeast Asia, stands out due to its superior tensile strength, which can reach up to 1760 MPa [13]. This characteristic makes abaca an attractive candidate for high-performance bio-composite applications, particularly in civil infrastructure.

The integration of abaca-fibers into polymer matrices to create NFPCs presents not only technical advantages in terms of strength-to-weight efficiency and energy-saving manufacturing processes, but also addresses the growing need for environmentally responsible construction practices [14–16]. Whereas several studies have examined the effectiveness of natural fibers in structural applications [17–19], research focusing specifically on the external confinement of cylindrical RC columns using abaca-based NFPC, particularly through spiral wrapping techniques, remains limited. This technique, which involves continuous helical wrapping of composite material around the column surface, has shown potential for enhancing both axial load capacity and ductility of RC columns. However, a comprehensive investigation into its structural behavior, including performance comparisons between different wrapping methods, is still lacking in current literature.

Therefore, this study aims to address this research gap by examining how the structure performs of cylindrical RC columns externally confined with abaca-fiber based NFPC sheets using two confinement techniques: spiral wrapping and partial wrapping. Through axial compression testing and comparative analysis with unconfined control specimens, the research explores the effectiveness of using abaca-based NFPC as an eco-friendly solution to strengthen and improve the ductility of RC columns. The findings are expected to contribute valuable insights toward the broader adoption of natural fiber composites in structural retrofitting applications. This investigation focuses on applying abaca fiber-reinforced NFPCs through spiral wrapping to externally confine short RC columns. The main goal is to assess the failure mechanisms, load-bearing capacity, and ductility of columns confined with abaca-fiber composites. It is expected that this approach will improve the axial load capacity and ductility, thereby highlighting the potential of NFPC composites in structural strengthening applications.

## MATERIALS AND METHODS

### Test object

Preparation of the reinforced concrete short column specimens began with a material investigation of the concrete and reinforcing steel. For the concrete, physical properties of the aggregate were evaluated to determine a suitable mix design capable of achieving a target compressive strength of 21 MPa. During casting, three standard cylindrical specimens were taken from the fresh concrete for compressive strength control testing. Tensile tests were also conducted on three specimens each of the main and transverse reinforcement bars, with diameters of diameter 10 mm and diameter 8 mm, respectively. In addition, one trial specimen and one standard specimen of the reinforced concrete short column were prepared and tested under unconfined axial compression to provide control data for comparison with the planned confined specimens. This approach follows standard practice in reinforced concrete structural experimentation. Consequently, only a single sample was required for each test condition involving confinement.

The experimental program involved short circular RC columns. There were three unconfined specimen using abaca fiber as the control group, referred to as Normal Reinforced Column Concrete (NC), and three specimen externally confined using partial wrapping and three specimen using spiral wrapping made of abaca-fiber-based CP-NFPC (Composite Partial Natural Fiber Polymer Composites) and CS-NFPC (Composite Spiral Natural Fiber Polymer Composites), respectively. Each column measured 205 mm in diameter and 615 mm in height. The longitudinal reinforcement consisted of six steel bars with a diameter of 10 mm, while the transverse reinforcement was provided by spirals with a diameter of 8 mm. For the CP-NFPC and CS-NFPC specimens, a single layer of NFPC was externally applied using the conventional wet lay-up method in accordance with ACI 440.2R-17 guidelines [20], with liquid resin as the bonding agent. The concrete mix exhibited a compressive strength of 21 MPa at 28 days. The test specimen was coated with white paint to enhance the visibility of crack patterns during the testing process. Additionally, the interface between the NFPC-confined region and the unconfined concrete surface was delineated to ensure a clear distinction between the respective zones. Table 1 provides the physical and mechanical properties of the reinforcing materials.

The partial wrapping configuration consisted of alternating reinforcement bands 123 mm wide. Meanwhile, the spiral wrapping configuration involved spirally wrapping bands 100 mm wide. For both CP-NFPC and CS-NFPC specimens, additional confinement bands 50 mm wide were applied at both the top and bottom ends of the columns to reduce the risk of failure at the loading interfaces. Figure 1(a-c) show the front and cross-sectional views of the NC, CP-NFPC, and CS-NFPC specimens, respectively.

### Test setup

Figure 2 shows the experimental setup used for the axial compression test. The tests were conducted using a hydraulic jack mounted on a loading frame, and the load applied was recorded through a calibrated load cell. Axial deformations were measured using two LVDTs connected to a data acquisition system. Strain data were collected from strain gauges placed on the longitudinal bars, spiral ties, and the external concrete surface at the mid-height of the columns.

The specimens were subjected to monotonically increasing axial loads until failure. Axial deformation and strain data were recorded at 0.5 kN load intervals throughout the loading process, up to the point of structural failure (Figure 3).

## RESULTS AND DISCUSSION

### Axial compressive strength

Based on the axial compressive strength test results of normal reinforced concrete short columns (NC) and externally confined specimens using partial wrapping (CP-NFPC) and spiral wrapping (CS-NFPC), with three specimens tested for each configuration, it can be observed that the axial compressive capacity of the specimens showed an increasing trend, with average compressive strength values of 746.23 kN, 838.62 kN, and 897.32 kN for NC, CP-NFPC, and CS-NFPC, respectively. Taking the NC configuration as the reference, the compressive strength capacity ratio increased by 1.13 and 1.22 for CP-NFPC and CS-NFPC, respectively. This indicates that external confinement using abaca fiber wrapping significantly influences the axial compressive strength capacity of short reinforced concrete columns. This can be seen in Figure 4, which presents the axial compressive test results of short columns for each variation. Further discussion regarding the behavior of each specimen is provided in the following section, where one representative sample is selected to reflect the general characteristics of the test specimens.

### Partially confined column performance

The unconfined specimen (NC) exhibited brittle failure characterized by vertical axial cracking that formed a triangular pattern at both ends (Figure 5). In contrast, the specimen partially confined with CP-NFPC showed irregular detachment of the concrete cover at mid-height, indicating the presence of confinement, although failure still occurred suddenly. The CP-NFPC specimen demonstrated a higher axial load capacity of 844.25 kN compared to 742.01 kN for the NC, representing a 13.79% improvement. It also exhibited greater deformation capacity, with an

**Table 1.** Physical-mechanical characteristics of the reinforcement materials [21]

| Parameter | Diameter (mm) | Thickness (mm) | Yield strength (MPa) | Ultimate strength (MPa) | Maximum strain (%) | Elastic modulus (GPa) | Density (kg/m$^3$) |
|---|---|---|---|---|---|---|---|
| Transversal steel - BjTP P8 | 8 | | 351.29 | 507.43 | 14.72 | 200 | 7.850 |
| Longitudinal steel - BjTS S10 | 10 | | 374.71 | 554.58 | 16.45 | 200 | 7.850 |
| Abaca-fiber sheet | 0.14 | 0.68 | | 1231.24 | 4.28 | 17,870.4 | |
| Epoxy-resin | | | 30 | | | 4.5 | 1300 |

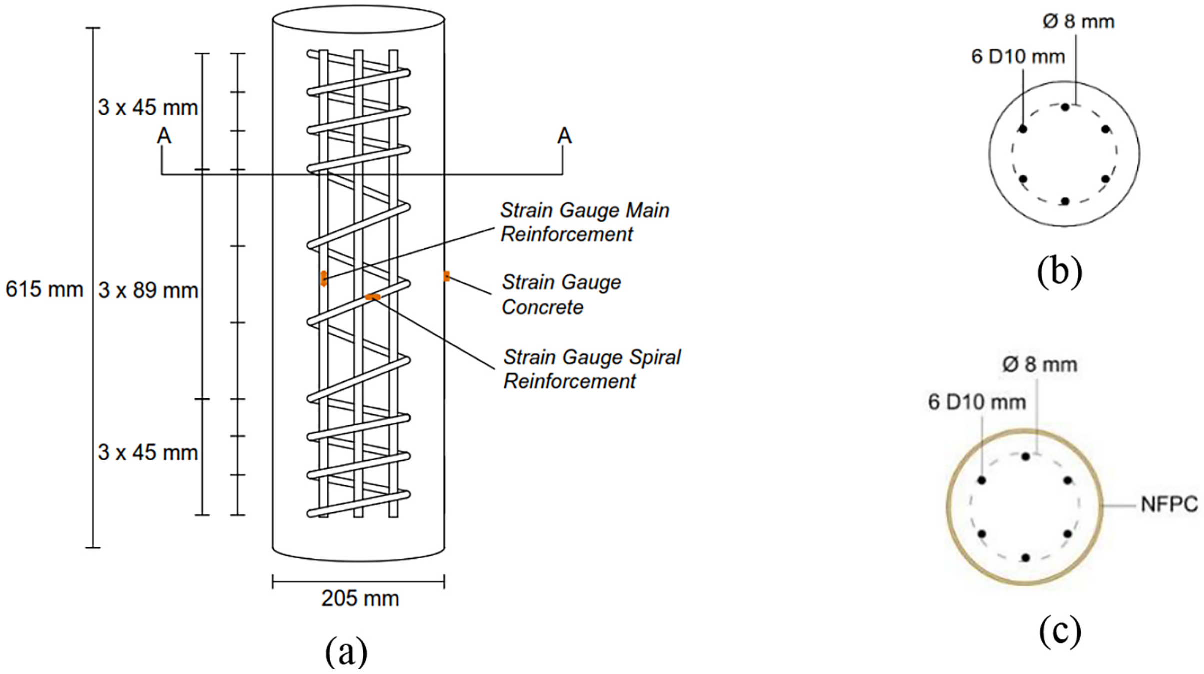
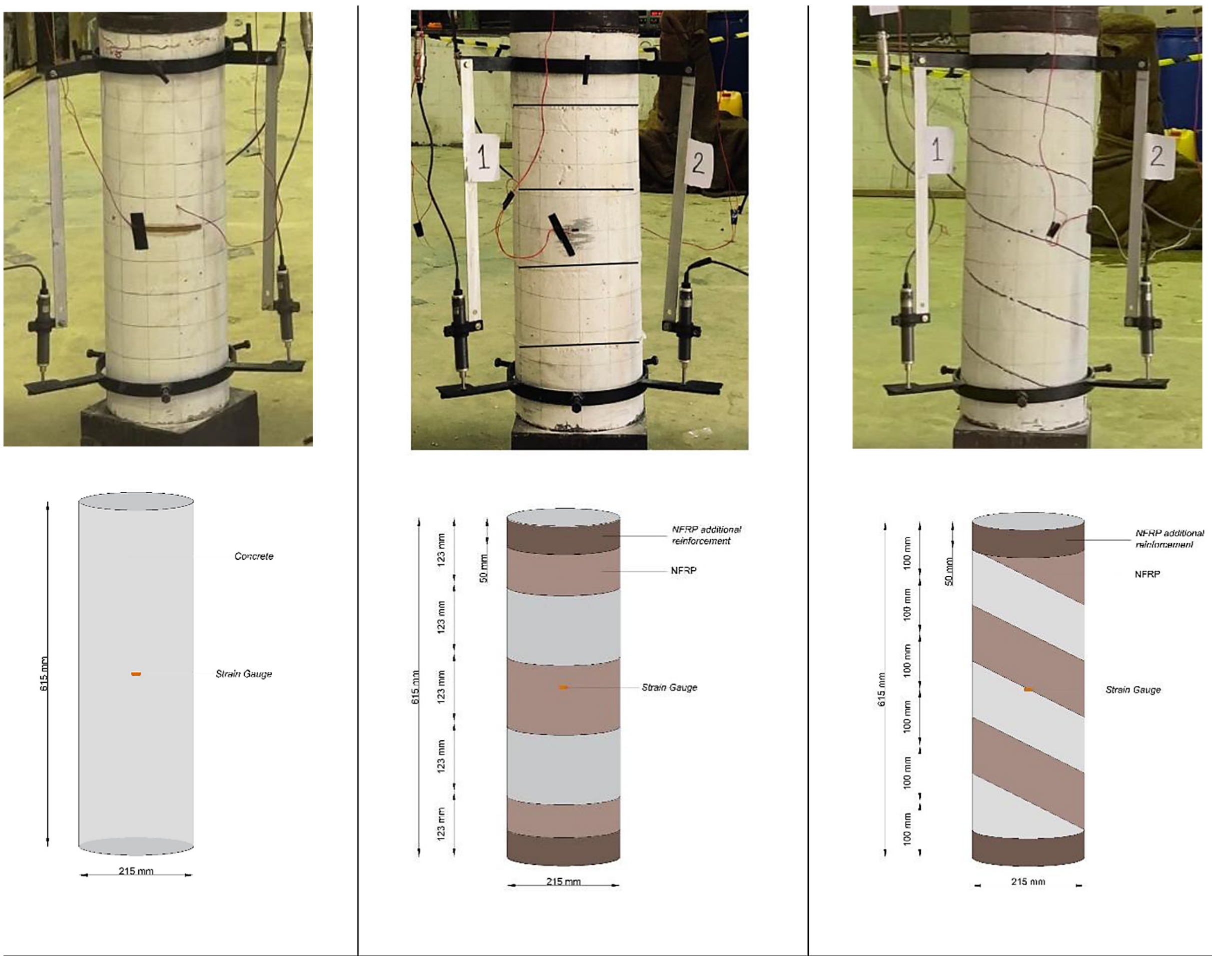



**Figure 1.** Specimen configuration and cross-sectional details: (a) specimen overview; (b) cross-section of NC; (c) cross section of CP-NFPC and CS-NFPC [21]




(a) (b) (c)

**Figure 2.** Short column samples: (a) NC; (b) CP-NFPC; (c) CS-NFPC [21]

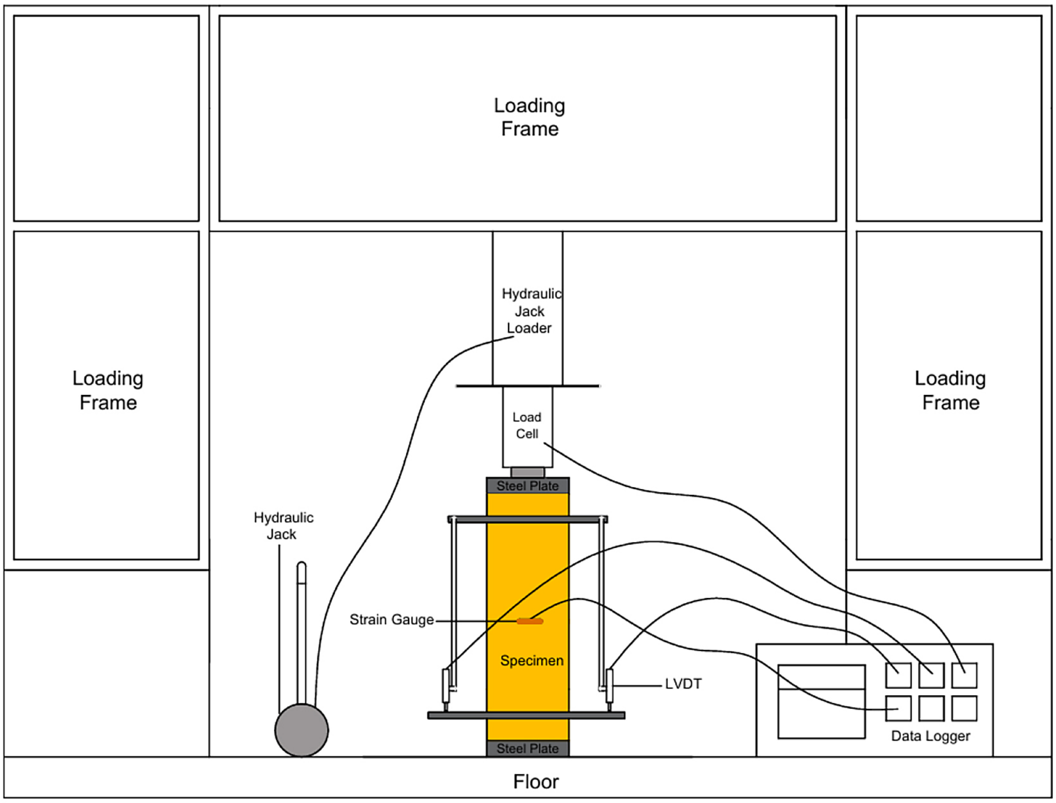



**Figure 3.** Test setup [21]

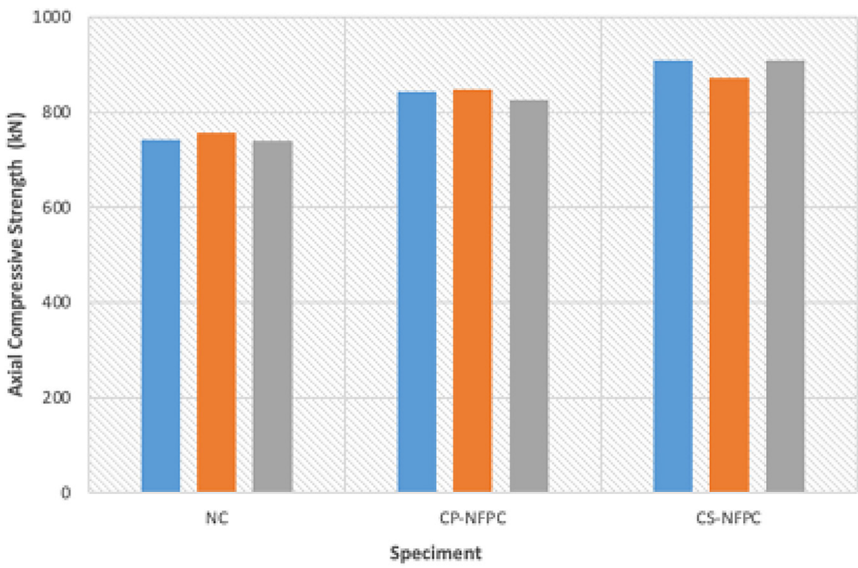



**Figure 4.** Axial compressive strength of specimen

axial displacement of 4.5 mm compared to 3 mm in the unconfined specimen, resulting in a 48% increase in ductility.

Both specimens reached yield at approximately 0,1873%ε. After yielding, the CP-NFPC specimen continued to gain axial load capacity and achieved a higher maximum strain of 4.7249%ε compared to 1.7290%ε in the NC specimen, further confirming enhanced ductility due to NFPC confinement. The transverse reinforcement in NC yielded after peak load at 0.347%ε, while in CP-NFPC, strain at failure was lower at 0.249%ε, indicating that the external NFPC wrapping reduced the demand on spiral reinforcement (Figure 6).

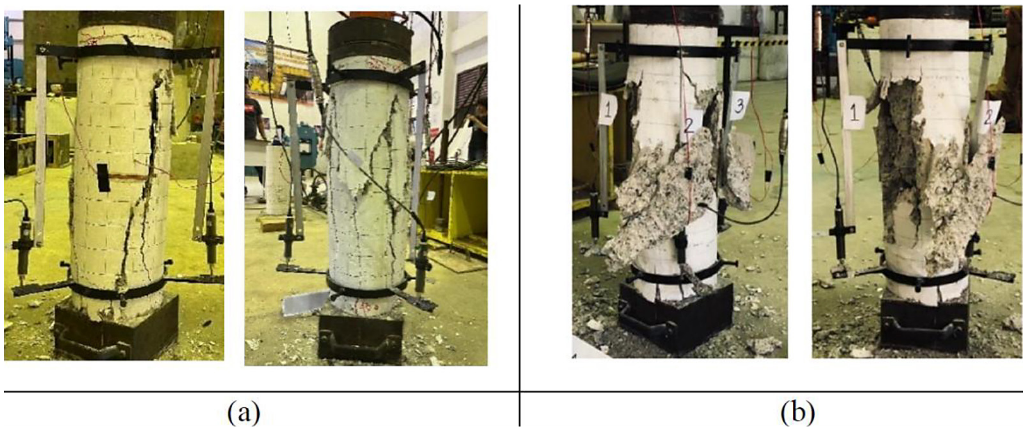



**Figure 5.** Failure mode samples of partially confined: (a) NC, and (b) CP-NFPC [21]

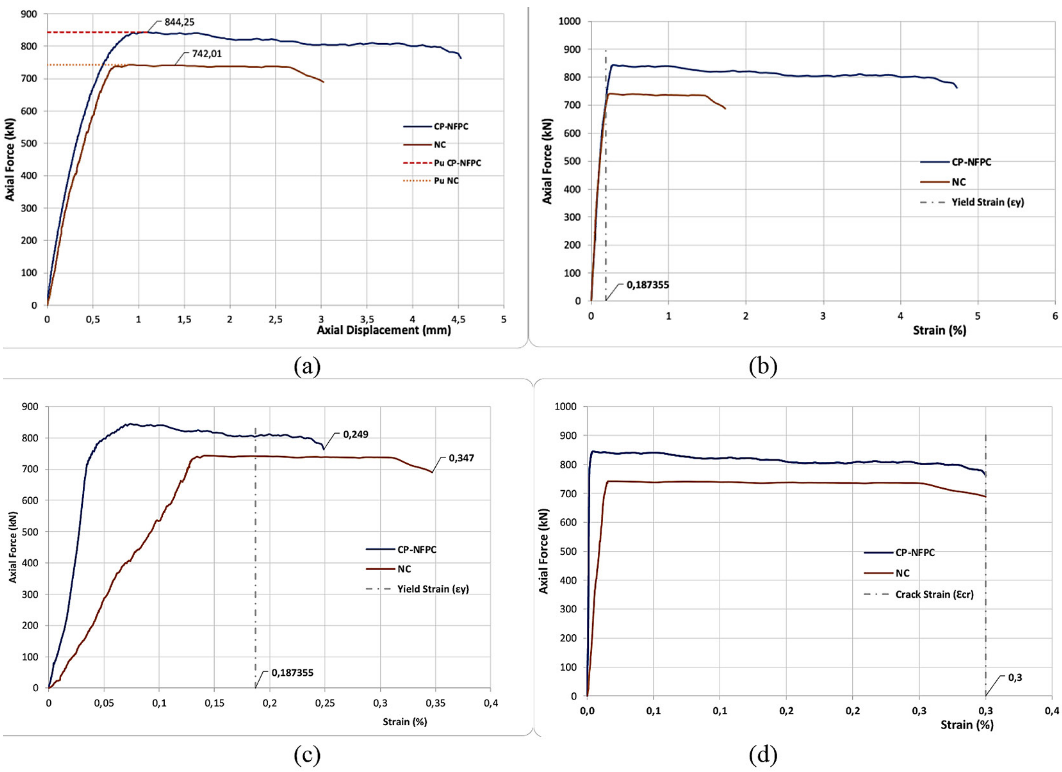
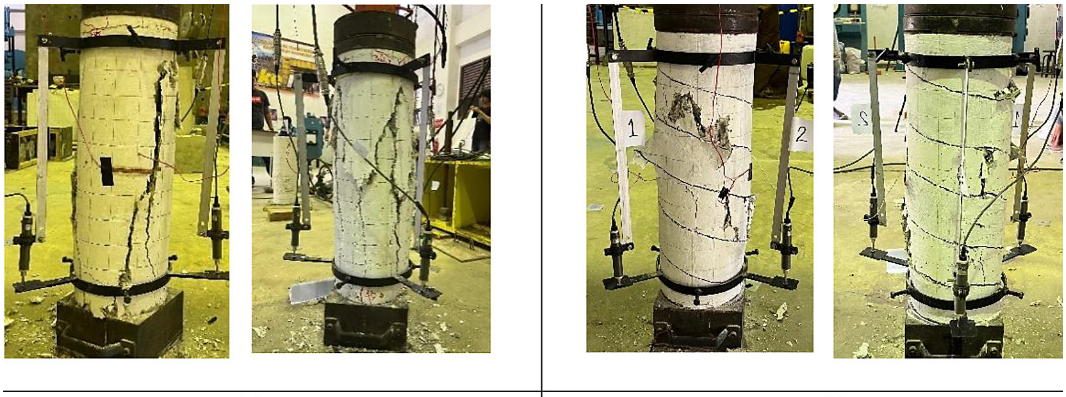



**Figure 6.** (a) axial load-axial displacement curves, (b) axial force vs longitudinal rebar strain, (c) axial force-tranversal spiral bar strain, and (d) axial force-concrete strain [21]

Concrete strain behavior was similar in both specimens, with failure occurring when strain reached approximately 0.3%ε, suggesting that compressive strength of the concrete was the primary factor in axial capacity, contributing approximately 76.7% of the total. Using the general yielding method, the ductility index (μ = Du/Dy) was calculated as 4.68 for NC and 6.91 for CP-NFPC, confirming a 48% enhancement in ductility. These results demonstrate that partial confinement using abaca-based NFPC significantly improves the ductile behavior of short reinforced concrete columns [21].

## Spiral confined column performance

As shown in Figure 7, the short column specimens exhibited different failure modes. The NC and CS-NFPC specimens displayed distinctly different behaviors. In Figure 6a, the NC specimen shows a vertical triangular crack pattern starting from both the top and bottom ends, indicating



(a) (b)

**Figure 7.** Failure mode samples: (a) NC, (b) CS-NFPC

a brittle failure once the maximum load was reached. Meanwhile, the CS-NFPC specimen experienced failure through irregular spalling of the abaca fiber wrapping around the concrete at the midsection of the specimen (Figure 6b), implying that while the NFPC provided confinement, the failure still occurred abruptly.

In this study, the axial load–displacement responses of the RC short columns are illustrated in Figure 8a. The results indicate that the short column with spiral CS-NFPC confinement exhibited a significantly higher axial compressive strength than the unconfined column NC, with peak load capacities of 910.27 kN and 742.01 kN, respectively. Compared to the unconfined specimen, the confined column showed a 22.68% increase in axial compressive strength. The load-displacement response followed a linear path up to the yielding of the longitudinal reinforcement bars. After yielding, stiffness progressively declined until the peak load was achieved. Following the maximum load, the column continued to displace without gaining additional load capacity, ultimately resulting in failure. The CS-NFPC specimen demonstrated a significantly higher deformation capacity, achieving an axial displacement of 14 mm, while the NC specimen only reached 3 mm. This represents a 374% improvement. These findings confirm the effectiveness of CS-NFPC in enhancing both the load-bearing capacity and deformation resistance of short columns.

The axial force and strain in the longitudinal reinforcement bars are shown in Figure 8b. While the graphs exhibit similar trends, the main differences are found in the ultimate load capacity (Pu) and the strain at failure. Both specimens show reinforcement yielding at a strain of 0.187355%. For the NC specimen, strain in the longitudinal reinforcement increases linearly up to the ultimate load (Pu), beyond which the strain continues to grow without an increase in load. On the other hand, the CS-NFPC specimen demonstrates a rise in ultimate axial load capacity (Pu) by approximately 150 kN after yielding, followed by a slight decrease in strain before failure. This indicates the CS-NFPC's contribution to confining the column and modifying the strain response. The confinement effect provided by the CS-NFPC significantly increased the strain at failure for the CS-NFPC specimen, from 1.7290% in the NC specimen to 4.3091%. This improvement underscores the role of NFPC confinement in enhancing the ductility of short columns, thus improving the performance and structural integrity of the composite material in reinforced concrete columns.

The axial force and strain in the transverse reinforcing bars are shown in Figure 8c, where distinct differences are observed in the behavior from the initial loading stage to the ultimate load (Pu) and failure strain. For the NC specimen, the transverse rebar remains elastic until the peak load is reached, with failure occurring at a strain of 0.7261%. Conversely, the CS-NFPC specimen shows significantly greater initial stiffness. The load-strain relationship stays linear until the longitudinal bars yield, and similar to the NC specimen, the transverse rebar only yields after the peak load is reached. However, the strain at failure for the CS-NFPC specimen is lower, at 0.3468%. This indicates that the external NFPC confinement improves the behavior of the transverse reinforcement, providing a more uniform confinement effect than in the NC specimen.

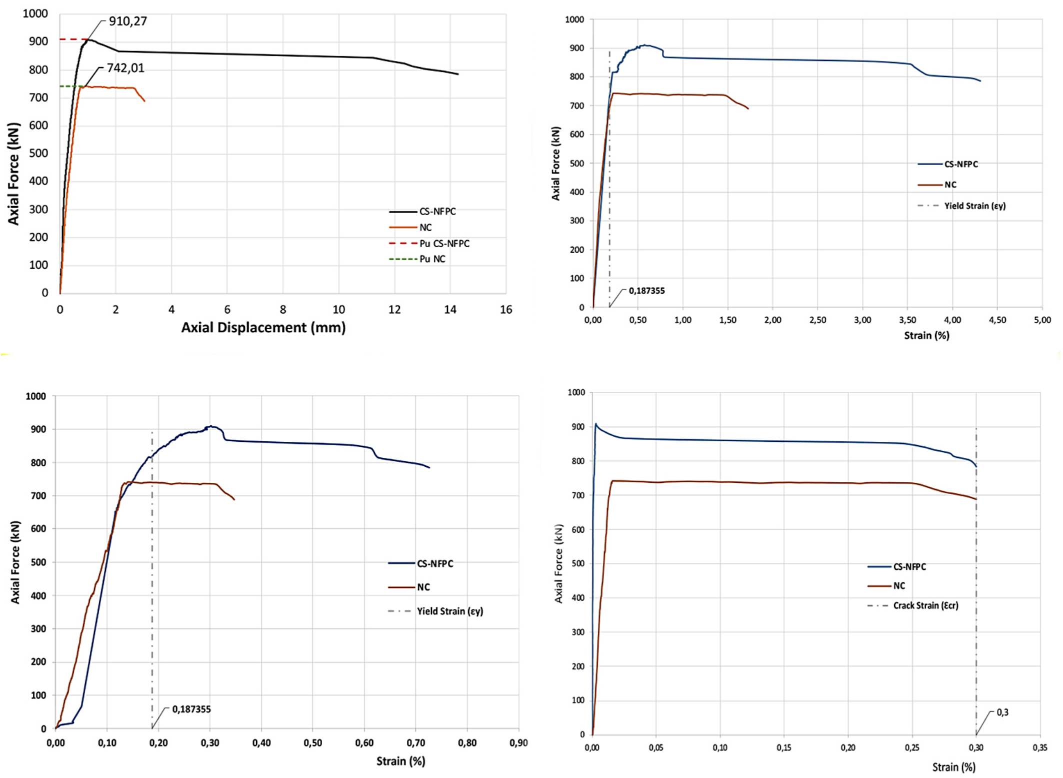



**Figure 8.** (a) axial load-axial displacement curves, (b) axial force vs longitudinal rebar strain, (c) axial force-tranversal spiral bar strain, and (d) axial force-concrete strain

**Table 2.** Results from the analytical analysis of the test samples

| Samples | Δu (mm) | Δy (mm) | μ (Δu/Δy) | Ratio μ |
|---|---|---|---|---|
| NC | 3.025 | 0.646 | 4.68 | 1 |
| Confinement partially CP-NFPC | 4.529 | 0.655 | 6.91 | 1.48 |
| Confinement spiral CS-NFPC | 14.274 | 0.683 | 20.90 | 4.47 |

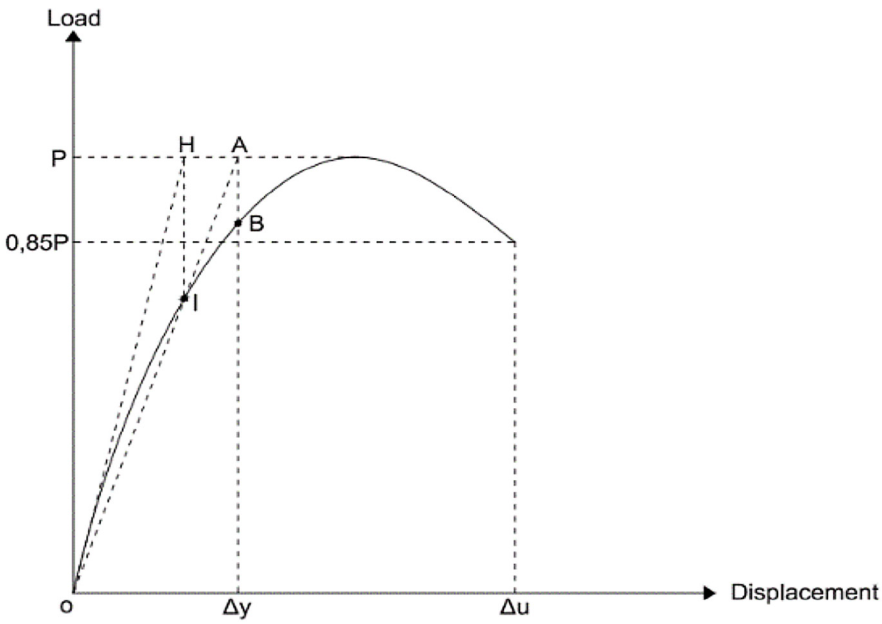



**Figure 9.** General yielding method [21]

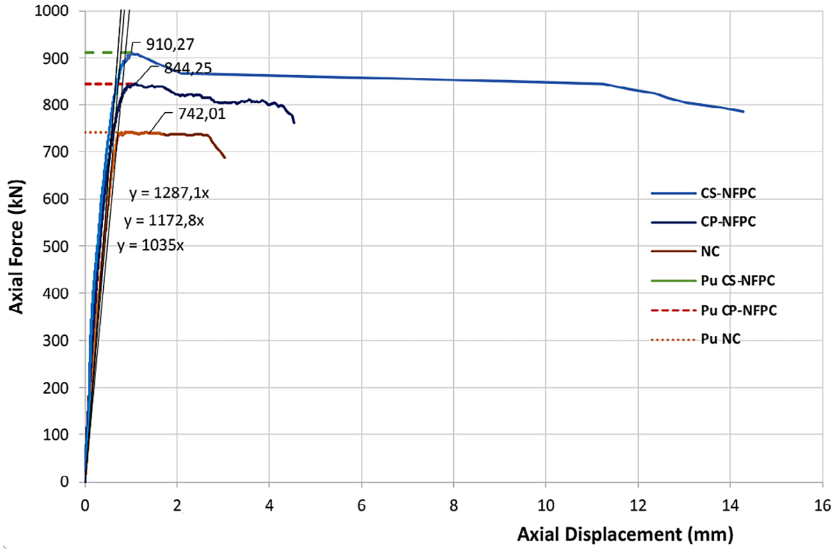



**Figure 10.** Axial load-axial displacement curves for NC, CP-NFPC and CS-NFPC

The strain patterns of the concrete cover for both test specimens display comparable behavior. As illustrated in Figure 8d, the strain curve for the CS-NFPC specimen is steeper during the initial loading phase in comparison to the NC specimen. The analytical calculations support this finding, indicating that the compressive strength of the concrete contributes to about 76.7% of the axial compressive strength capacity of the short reinforced concrete column.

The axial load at yield (Py), the corresponding axial displacement of the main reinforcement at yield, and the ultimate axial displacement for both test specimens were determined using the general yielding method [22, 23]. This method, as depicted in Figure 9, identifies Point H, where the line of elastic behavior intersects the peak strength. A vertical line through Point H intersects the load-displacement curve at Point I. The secant line drawn from Point O to Point I crosses the peak strength at Point A, defining the yield displacement.

The analytical results showed that the ductility index (μ), calculated as the ratio of u/y (with u being ultimate displacement and y being yield displacement), is 4.68 for the NC specimen and 20.90 for the CS-NFPC specimen (Table 2). This indicates a 347% increase in ductility due to the spiral NFPC confinement in short columns (Figure 10).

## CONCLUSIONS

The failure modes, axial load capacity, and ductility of short concrete columns externally confined with abaca-fiber-based NFPCs were evaluated in this study. The results highlight the effectiveness of NFPC confinement in improving structural performance. Based on the experimental findings, the following conclusions can be drawn:

1. Partial wrapping – partial confinement using abaca NFPC significantly improved the axial compressive capacity and ductility of short concrete columns. Specifically, the axial load capacity increased by 13.8%, while ductility improved by 48%. These results suggest that even limited external confinement with abaca-fibers can positively influence structural behavior. Future studies are recommended to explore full-wrap configurations using spiral wrapping techniques and varying the number of layers to optimize confinement efficiency.
2. Spiral wrapping – spiral wrapping with abaca NFPC provided greater enhancements, with an observed increase in axial compressive capacity of 22.68% and a substantial improvement in ductility by 347%. These results underscore the superior performance of spiral wrapping methods in comparison to partial wrapping. Further research should focus on full-coverage spiral wrapping using multiple layers to maximize the compressive strength and ductility of short concrete columns.
3. By comparing the axial compressive strength and displacement ratio (P/δ) within the elastic range from the test results of the three specimens as shown in Figure 11, it is evident that the stiffness of the specimens increased with

the application of NFPC confinement. Sequentially, the stiffness values within the elastic range for the NC, CP-NFPC, and CS-NFPC specimens were 1035 kN/mm, 1172 kN/mm, and 1287 kN/mm, respectively. In other words, the partial and spiral confinement configurations provided stiffness values of 1.13 and 1.34 times greater than that of the unconfined normal reinforced concrete short column specimen.

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