

Carbon Fiber-Reinforced Polymer (CFRP) Confinement Strategies for Concrete Columns: Evaluating the Efficacy of Full and Partial Wrapping Methods

Saci Dahmani¹, Nour El Houda Khitas², Riad Babba¹, Kamel Hebbache², Abdellah Douadi^{2,3}, Mourad Boutlikht², Abdelraouf Messai², Cherif Belebchouche²

¹Faculty of Science and Technology, University of Tamanghasset, Tamanghasset 11001, Algeria

²Civil Engineering Research Laboratory of Sétif (LRGCS), Department of Civil Engineering, Ferhat Abbas University of Sétif 1, Sétif 19000, Algeria

³Emergent Materials Research Unit (EMRU), Department of Civil Engineering, University Ferhat Abbas Setif 1, Setif 19000, Algeria

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Abstract: This study evaluates the effectiveness of full and partial fiber-reinforced polymer (FRP) confinement techniques on concrete columns, with a focus on carbon fiber-reinforced polymers (CFRP). Experimental results revealed that full CFRP confinement markedly improves both compressive strength and ductility. Specifically, columns fully confined with CFRP exhibited a maximum increase in compressive strength of 89.36% compared to unconfined specimens. In contrast, partial confinement using horizontal strips with a 30 mm spacing resulted in a 49.53% increase in compressive strength, though this was 21.03% less than that achieved with full confinement. Spiral confinement, with spacings of 45 mm and 65 mm, achieved strength increases of 3.03% and 6.58%, respectively, with a maximum enhancement of 21.90% compared to unconfined concrete. Deformation results showed that horizontal strips enhanced ultimate axial deformation by up to 610.78%, whereas spiral confinement improved deformation by 591.42% at 30 mm spacing. The study concludes that horizontal CFRP strips provide superior performance and efficiency for strength enhancement compared to spiral confinement. These findings indicate that partial CFRP confinement is a viable alternative to full confinement, offering substantial improvements in concrete strength and deformation while optimizing material use and installation complexity.

Keywords: CFRP, Concrete Columns, Full Confinement, Partial Confinement, Compressive Strength, Ductility, Structural Performance.

1. Introduction

In recent decades, fiber-reinforced polymers (FRP) have become an increasingly prevalent solution for enhancing the structural performance of concrete columns. FRP materials [1-3], which include carbon, glass, and aramid fibers embedded in a polymer matrix, have been recognized for their ability to significantly increase both the compressive strength and ductility of concrete [4, 5]. This enhancement is primarily due to the FRP's capacity to provide a confining pressure that delays crack initiation and inhibits the propagation of micro-cracks [6], thus transforming the failure mode of concrete from brittle to ductile [7]. The application of FRP not only extends the service life of aging infrastructure but also offers an effective means for retrofitting structures to meet higher load requirements or comply with updated seismic design standards [8-10].

Historically, research on FRP reinforcement for concrete columns has focused on full wrapping techniques [11, 12]. In these methods, columns are completely encased in FRP composites along their longitudinal axis [13]. This approach ensures continuous confinement, which results in uniform stress distribution across the entire column and mitigates localized failure [14]. Numerous studies have demonstrated that full confinement can significantly improve the load-carrying capacity, ductility, and energy absorption of concrete columns [14]. Full wrapping is particularly effective in seismic

applications where the ability to withstand both axial compressive loads and lateral deformations is critical [15].

Despite the well-documented benefits of full confinement, practical implementation often faces constraints such as cost, accessibility, and architectural challenges[6] . As a result, recent research has increasingly focused on partial confinement strategies [16-18], where FRP is applied in strips or bands at intervals along the height of the column [19]. Although partial confinement does not provide the same level of continuous confinement as full wrapping, it has been shown to offer substantial strengthening benefits while reducing material usage and installation complexity. For instance, studies have indicated that CFRP strips spaced at regular intervals can enhance the load-carrying capacity of columns by over 30% compared to unconfined columns[20] . The effectiveness of partial confinement is closely related to the spacing and orientation of the strips, with tighter spacings generally providing better performance [21-23].

However, despite the progress in understanding partial confinement, the research in this area remains relatively limited compared to the extensive body of work on full confinement. While horizontal CFRP strips have been extensively studied, other configurations, such as spiral or diagonal arrangements, are less explored. Furthermore, the long-term behavior of partially confined columns under sustained loads, cyclic loading, or environmental degradation has not been thoroughly investigated [24]. These factors are crucial for ensuring the durability and reliability of partial confinement methods in practical applications.

The primary objective of this study is to advance the understanding of the effects of partial CFRP confinement on the mechanical properties of concrete columns. Specifically, the research focuses on two modes of partial confinement: horizontal strip confinement and spiral confinement. By comparing these configurations with both unconfined and fully confined columns, the study aims to evaluate their performance in terms of failure modes, stress-strain behavior, and ultimate axial stress and strain values

2. Materials and Methods

In this study, ordinary concrete was utilized. It was prepared and cast at the Civil Engineering Research Laboratory of SÉTIF 1 University and the Emerging Materials Research Unit at Ferhat Abbas University, SÉTIF 1. The concrete mix included crushed aggregates with a maximum size of 15 mm and fine aggregates passing through a 3 mm sieve (Table 1). The average compressive strength of the cylindrical specimens was $f_{co}=21.42\text{MPa}$, with a corresponding strain of $\epsilon_c=0.408\%$

The reinforcement employed was the "SikaWrap-230C/45" carbon fiber fabric, with its properties provided in (Table 2). The adhesive used was "Sikadur-330" epoxy resin, mixed at a 1:4 ratio (epoxy hardener: resin), as specified in (Table 3).

Table 1. Mix Proportions and Characteristics of the Concrete Used.

Component	Quantity (kg/m ³)
Cement	210
Water	115.5
Crushed Aggregate Ø 3/8	218.68
Crushed Aggregate Ø 8/15	977.06
Sand Ø 0/3	847.24
Water-to-Cement Ratio (W/C)	0.55
Compressive Strength, f_{co} (MPa)	21.42
Ultimate Strain, ϵ_{co} (%)	0.761

Table 2: Properties of SikaWrap-230C/45 Fabric

Property	Value
Tensile Strength (MPa)	4,300
Tensile Modulus (MPa)	234,000
Ultimate Elongation (%)	1.8
Fiber Density (g/cm ³)	1.76
Fabric Thickness (mm)	0.13

Table 3: Properties of Sika Dur 330 Resin

Property	Value
Density (g/cm ³)	1.30
Tensile Strength (MPa)	> 30
Bond Strength to Concrete (MPa)	> 4

Elastic Modulus (MPa)	
- Flexural	3,800
- Tensile	4,50

The mechanical properties of the CFRP composite (fabric + resin) were determined through coupon testing in accordance with NF EN ISO 527 standards (recommendations 1, 2, and 5) (Table 4).

Table 4: Mechanical Properties of CFRP Composite

Property	Value
Thickness of CFRP Composite t_r (per layer) (mm)	1
Elastic Modulus E_{fr} (MPa)	34900
Tensile Strength f_{pr} (MPa)	480
Ultimate Strain ϵ_{ru}	2%

A total of cylindrical concrete specimens, 320 mm in height and 160 mm in diameter, were prepared and organized into eight groups. The confinement methods included full confinement and partial confinement with horizontal and spiral CFRP strips. For partial confinement, variables such as strip spacing, orientation relative to the horizontal axis, and the amount of CFRP material were examined. A consistent strip width of 30 mm was used, while spacings of 30, 45, and 65 mm were tested for both horizontal and spiral configurations. Partially spiral-confined specimens also had additional end confinement with 20 mm wide CFRP strips.

Specimen designations were based on an alphabetical system, where each letter represented the type of confinement, method, mode, and strip spacing, respectively. Confinement arrangements are detailed in Figures 1.

Compression tests were conducted using a 3000 kN MCC8 universal testing machine, with a load-controlled rate of 0.5 MPa/s, following standard procedures. Strip positions were marked using tape on the concrete surface. Specimens were capped with high-strength sulfur to ensure proper contact between the load cell and the specimen. Axial displacement was measured with three linear variable differential transformers (LVDTs) positioned at mid-height.

All confined specimens were overlapped by 150 mm, following the SikaWrap-230C/45 fabric technical datasheet. They were allowed to cure at room temperature under laboratory environmental conditions for 7 days to ensure the epoxy reached its full strength before testing.

The abbreviations used to distinguish the series are as follows:

NC: Non-confined cylinders.

CT: Cylinders fully confined with one layer.

For partially confined series, the nomenclature is divided into three parts: the first part is CP for partially confined, the second part is H or I for horizontal or inclined (spiral) strips, respectively, and the third part is a number indicating the spacing (in mm) between the strips (30, 45, or 65 mm). For example, CPH45 denotes specimens partially confined with horizontal strips spaced 45 mm apart.



Figure 1 : Aspect des différents groupes partiellement confinés

3. Results and discussion

Failure mode

The groups exhibit various typical failure modes, as illustrated in Figure 2:

Non-confined cylinders (NC): Damage began with inclined cracks in the concrete, leading to a failure mode characterized by concrete crushing (Figure 2-a).

Fully confined cylinders (CT): Failure of the CFRP was localized at mid-height. The concentration of lateral confinement led to sudden CFRP rupture, followed by a significant explosion (Figure 2-b).

Partially confined cylinders with 65 mm spacing (CPH65 and CPI65): These specimens generally failed due to concrete crushing. Cracks developed between adjacent CFRP strips as the average axial stress approached the strength of the unconfined concrete. The failure mode was predominantly characterized by cracking with diagonal shear failure (Figures 2-c and 2-d).

Partially confined cylinders with horizontal or spiral CFRP strips (CPH30, CPI30, CPH45, and CPI45): These specimens experienced CFRP strip rupture due to tensile stress at mid-height (Figures 2-e to 2-h). Failure was observed in the concrete core, which disintegrated in a conical cracking mode.

Cylinders subjected to compression: The failure was sudden and explosive following CFRP composite rupture. Notably, the concrete that was torn away adhered to the CFRP composite, indicating good adhesion between the CFRP and concrete (Figure 2). Intact strips were observed in several specimens post-explosion.

Additionally, CFRP rupture did not occur at the ends of the cylinders due to extra friction from the loading platens near both ends, as explained by Teng et al. (2015b).

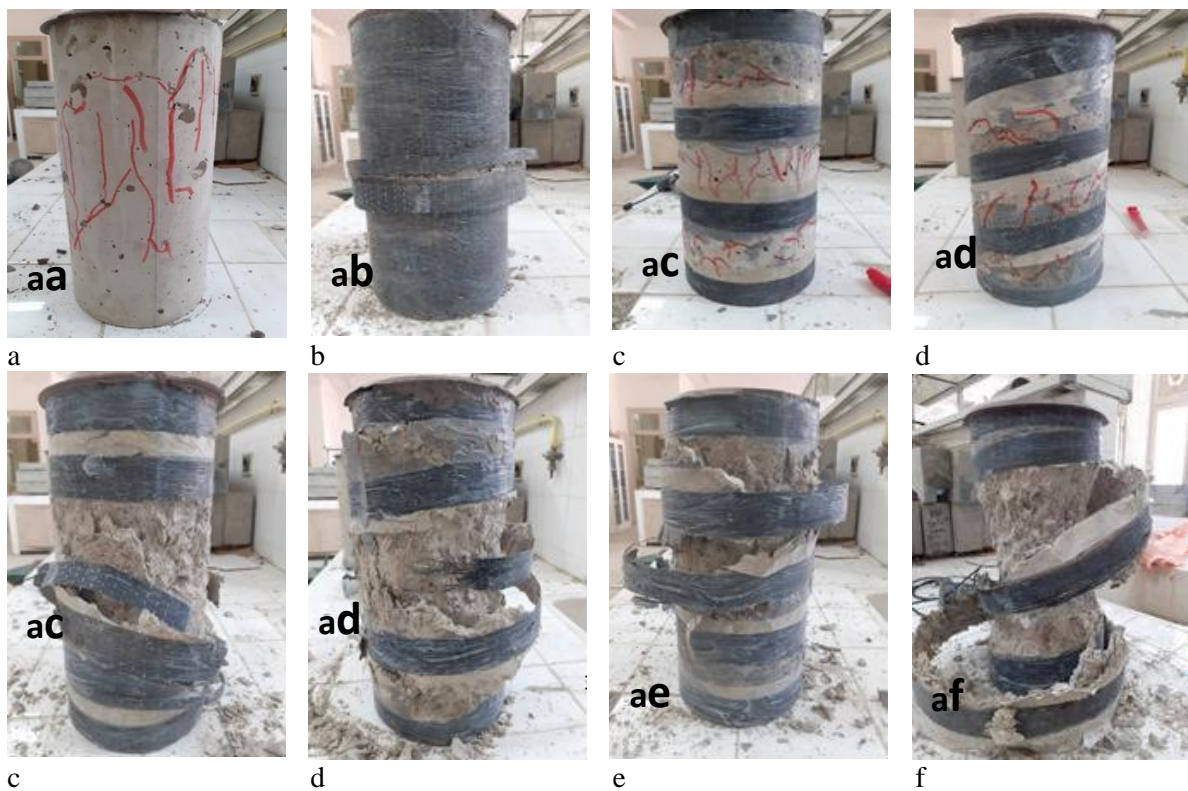


Figure 2: Failure Modes of Specimens

Stress-Strain Behavior of a Concrete Cylinder Partially Confined by Horizontal CFRP Strips

Figure 3 illustrates the stress-strain response for all studied groups. Axial deformations were measured using LVDTs. Therefore, the axial deformations shown in Figure 3 were derived from readings taken by the three LVDTs positioned at mid-height, as recommended by several researchers (Chen et al., 2016; Zeng et al., 2018).

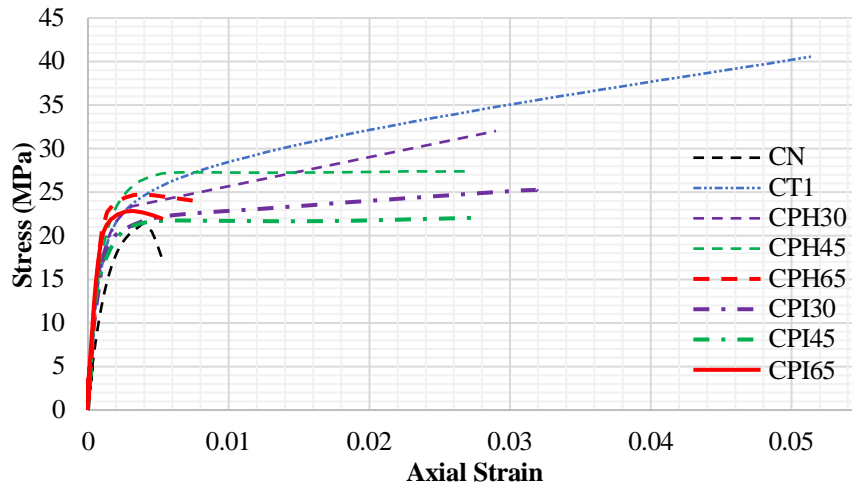


Figure 3: Stress-Strain Curves of All Groups

Figure 3 presents the stress-strain curves for fully confined cylinders using CFRP composites. These curves show an initial ascending portion followed by a second branch where stress softening begins.

In contrast, the stress-strain behavior for partially confined concrete is different, as illustrated in Figure 4. These curves typically exhibit a bilinear trend with hardening up to failure (CFRP rupture). Initially, the curves are linear, dominated by the strength of the unconfined concrete, indicating that the CFRP confinement has not yet been activated due to negligible lateral expansion. As the concrete undergoes lateral expansion and increased deformations, the response becomes nonlinear. CFRP confinement applies lateral pressure after reaching the ultimate strength of the unconfined concrete ($f_{co} = 21.42$ MPa), leading to the formation of additional cracks and a reduction in concrete stiffness.

For specimens with horizontal CFRP strips spaced 30 mm apart, the stress continued to rise linearly with a gradual slope until failure ($f_{cc} = 32.03$ MPa) (Figure 4). The concrete was fully cracked, and CFRP confinement was activated, enhancing load capacity and significantly increasing compressive strength and ductility.

Specimens partially confined with horizontal CFRP strips spaced 45 mm apart displayed a bilinear stress-strain trend with substantial ductility, maintaining a constant slope until failure at 27.4 MPa (Figure 4). The final stress at failure was significantly higher than the unconfined concrete strength, indicating adequate confinement.

For specimens with strips spaced 65 mm apart (Figure 4), the stress-strain curves showed a descending branch with observable stress softening up to failure. The concrete withstood a portion of the axial load after reaching a maximum strength of 24.71 MPa. However, strength decreased until failure occurred at 23.84 MPa, which was slightly above the unconfined concrete strength ($f_{co} = 21.42$ MPa). Thus, the level of confinement was still considered adequate.

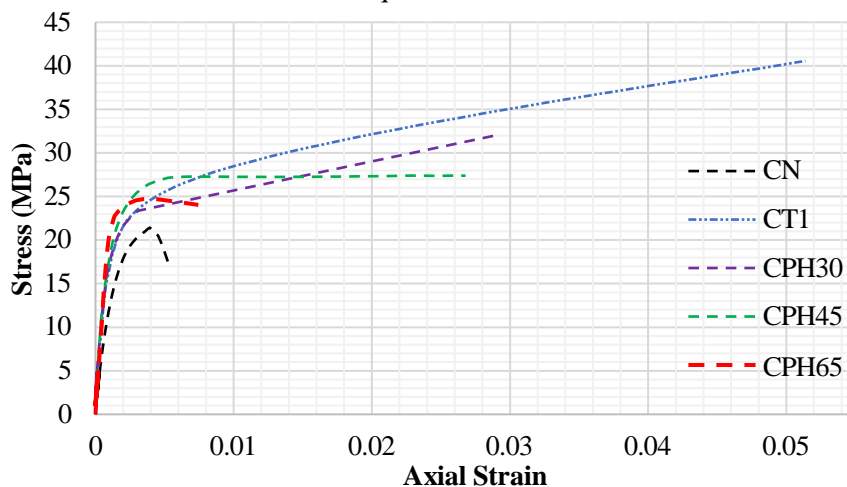


Figure 4: Stress-Strain Curves of Horizontally Confined Groups

Stress-Strain Behavior of a Concrete Cylinder Partially Confined with Spiral CFRP Strips

Figure 5 compares the stress-strain curves of partially confined cylinders with CFRP strips inclined relative to the horizontal. Each group features different spacings between the CFRP strips, leading to varying angles of inclination, allowing for a direct comparison between series.

As shown in Figure 5, the stress-strain behavior of these specimens initially evolved linearly, similar to unconfined samples. For specimens with spacings of 30 mm and 45 mm, the stress-strain curves exhibited a bilinear trend with significant deformation softening up to failure. The final stress at failure was slightly higher than the ultimate strength of unconfined concrete.

For specimens with inclined CFRP strips spaced 65 mm apart (CPI65), the stress-strain curves displayed a short descending branch up to failure, where deformation softening was observed. These curves are similar to those of the specimens with horizontal CFRP strips spaced 65 mm apart (CPH65).

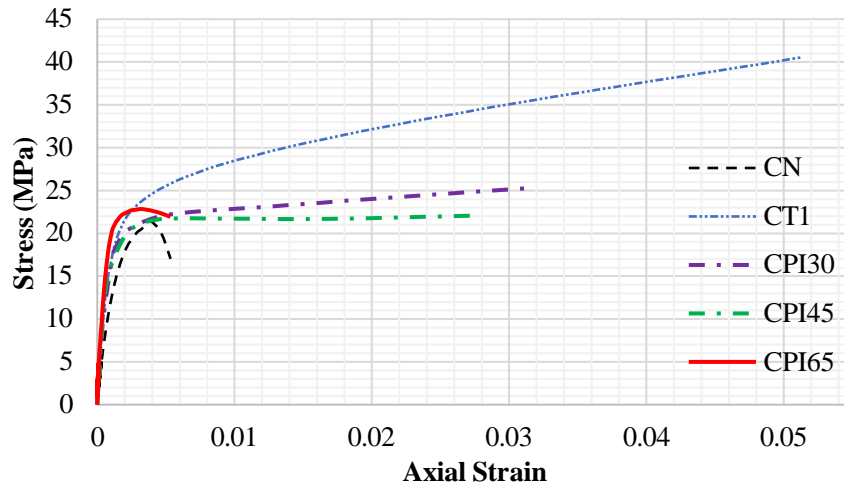


Figure 5: Stress-Strain Curves of Spirally Confined Groups

Figures 3 to figure 5 illustrate that the stress-strain curves for CFRP-confined concrete exhibit two typical segments, with either an ascending or descending second part. For most specimens, the axial stresses increase monotonically until failure, whereas only the stress-strain curves of the specimens with horizontal and inclined CFRP strips spaced 65 mm apart (CPH65 and CPI65) show a descending branch. The relatively low volumetric ratios of CFRP applied in these two series are insufficient for achieving a monotonically ascending stress-strain behavior. The volumetric ratio of CFRP is defined as ρ_f [25].

$$\rho_f = \frac{A_{FRP}D}{(\pi D^2/4)} = \frac{4b_f n t_f}{DS} \quad (1)$$

For specimens with a 65 mm spacing, the level of confinement approaches the threshold of insufficient confinement, resulting in a reduced increase in strength. In contrast, specimens with adequate confinement, achieved with smaller spacings (30 mm and 45 mm), show significantly improved compressive strength and ultimate deformation due to the more effective confinement.

Effect of Strip Spacing on Partial Confinement

Table 5 summarizes the average compressive strength values and deformations for all studied samples. It is evident that both partial and full CFRP confinements significantly enhance the ultimate compressive strength of the specimens compared to unconfined samples. Fully CFRP-confined cylinders exhibited the highest strength improvement, achieving an increase of 89.36%.

Among the partially confined specimens, those with horizontal CFRP strips spaced 30 mm apart demonstrated the most significant improvement, with a 49.53% increase in compressive strength compared to unconfined samples. This result indicates that the strength of partially confined CFRP samples is approximately 21.03% lower than that of fully confined CFRP samples. However, this difference is marginal relative to the material savings achieved. Additionally, this configuration showed a 610.78% increase in axial deformation compared to unconfined samples, though this is 43.56% lower than the deformation observed in fully confined CFRP samples.

The effect of increased horizontal spacing on maximum deformation was also evident. Specimens with 45 mm and 65 mm spacing showed increases in displacement of approximately 556.48% and 106.40%, respectively.

For cylinders confined with spiral CFRP strips, the compressive strength results were more challenging to interpret. The strength increased by 3.03% with a 45 mm spacing and by 6.58% with a 65 mm spacing. Although these values were lower compared to those with horizontal CFRP strips, a maximum strength

increase of 21.90% over unconfined concrete was recorded. The relationship between spiral spacing and ultimate deformation was also clear. Displacement increased with reduced spacing between spiral bands, with deformations rising by 591.42% at 30 mm spacing, 572.67% at 45 mm, and 30.47% at 65 mm spacing. Unconfined concrete had a deformation of 0.00408, whereas the highest deformations were 0.0514 for fully confined specimens and 0.029 for all partial confinement configurations.

Table 5: Summary of Experimental Results Compared to Unconfined Cylinders

ID	Stress (MPa)		Strain	
	f_{cc}	Improvement	ϵ_{cu}	Improvement
CT	40,56	89,36%	0,051381	1159,34%
CPH30	32,03	49,53%	0,029	610,78%
CPH45	27,4	27,92%	0,026784	556,48%
CPH65	24,71	15,36%	0,008421	106,40%
CPI30	26,11	21,90%	0,02821	591,42%
CPI45	22,07	3,03%	0,027445	572,67%
CPI65	22,83	6,58%	0,005323	30,47%

Influence of Strip Orientation

Figures 6 to figure 8, along with Table5, illustrate the impact of CFRP strip inclination on performance. Comparisons between CPH30 and CPI30, CPH45 and CPI45, as well as CPH65 and CPI65, indicate that horizontal CFRP strips generally provide greater improvements compared to inclined strips. Ultimate deformations increased as the angle between the CFRP strips and the horizontal decreased. However, specimens confined with spiral CFRP strips showed a smaller increase in strength compared to those confined with horizontal strips. This observation is attributed to reduced lateral pressure effectiveness due to the orientation of the fibers, which was less effective in limiting the lateral expansion of the concrete.

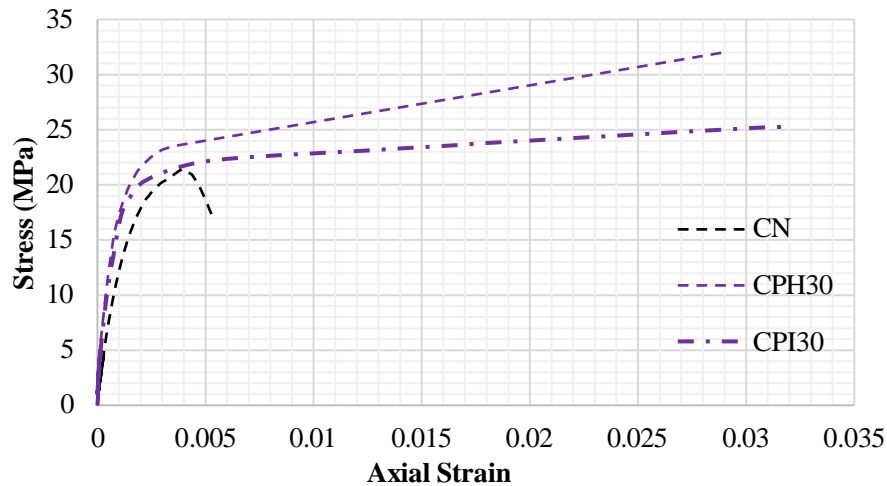


Figure 6: Stress-Strain Curves of Groups Confined with 30mm Spacing

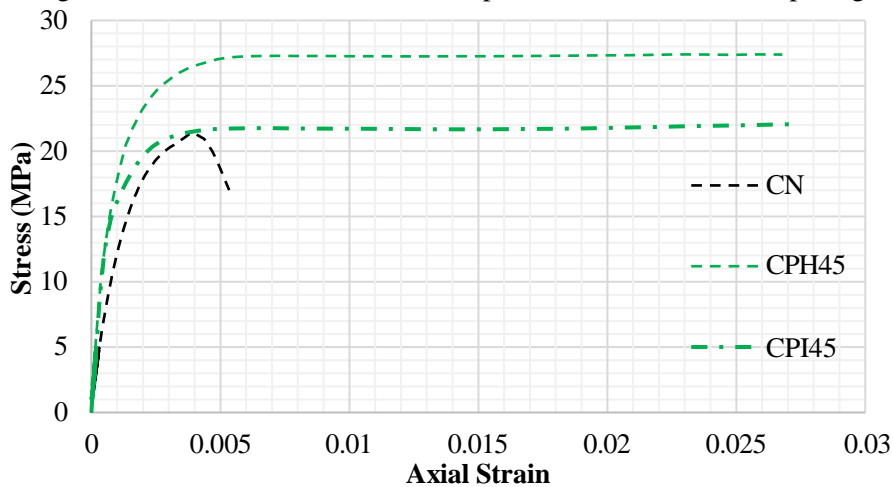


Figure 7: Stress-Strain Curves of Groups Confined with 45mm Spacing

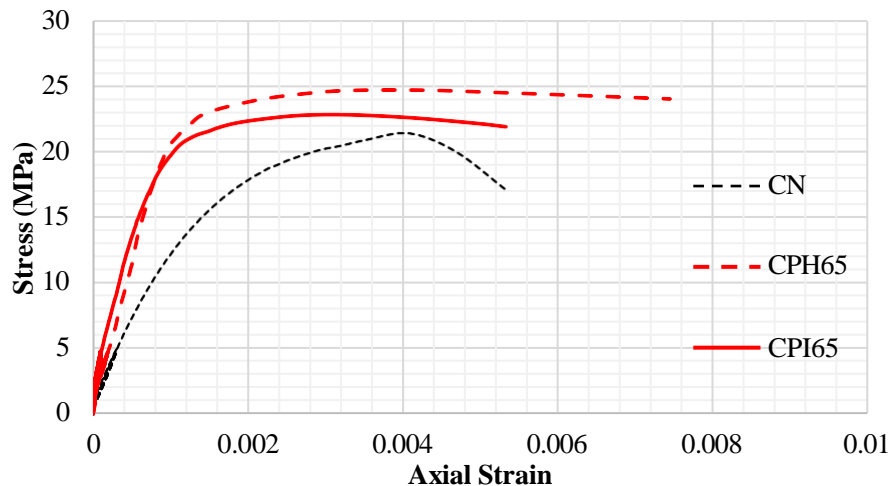


Figure 8: Stress-Strain Curves of Groups Confined with 65mm Spacing

4. Conclusion

This study investigated the impact of CFRP (Carbon Fiber Reinforced Polymer) confinement on the compressive strength and deformation behavior of concrete cylinders. The results highlight the effectiveness of both full and partial CFRP confinement techniques, with a focus on comparing different configurations and their practical implications.

Full CFRP Confinement: Cylinders with full CFRP confinement exhibited a substantial increase in compressive strength, up to 89.36% higher than unconfined specimens. This method provides the highest performance and is effective for achieving maximum strength enhancement.

Partial Confinement with Horizontal CFRP Strips: Specimens with horizontal CFRP strips at a 30 mm spacing showed a 49.53% improvement in compressive strength. This method demonstrated nearly comparable performance to full confinement while using approximately half the amount of CFRP material, indicating its efficiency.

Partial Confinement with Spiral CFRP Strips: The use of spiral CFRP strips resulted in less significant strength improvements. For instance, the CPI45 specimens showed a 45.59% decrease in strength gain compared to fully confined specimens. This suggests that spiral strips are less effective than horizontal strips in providing lateral support.

Effectiveness Comparison: Horizontal CFRP strips proved to be more effective in enhancing lateral confinement and overall performance compared to spiral strips. This makes them a more practical choice for partial confinement applications.

Cost-Effectiveness: Partial confinement using horizontal CFRP strips offers a cost-effective alternative by achieving substantial improvements in both compressive strength and deformation capacity while utilizing less material.

Future research should explore the long-term durability of CFRP confinement in various environmental conditions and loading scenarios. Additionally, investigating alternative CFRP configurations and hybrid reinforcement methods could further optimize performance and material usage. Studies could also focus on the economic feasibility of implementing these confinement techniques in real-world construction projects, considering both material costs and structural benefits.

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