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ORIGINAL PAPER

The influence of small fiber deviation on the behavior of CFRP confined concrete cylinders: an experimental study

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Abstract

The effectiveness of Fiber Reinforced Polymer (FRP) jackets in confining concrete columns significantly depends on fiber orientation. Most design guidelines limit the deviation angle from the hoop direction to 5°, yet this limitation lacks sufficient experimental justification, particularly for small deviation angles (<15°). Moreover, in practical applications, small deviation angles may accidentally occur due to workmanship errors or construction limitations, which further highlights the need for investigation. To address this gap, the present study experimentally investigates the influence of small fiber deviation angles on the performance of FRP-confined concrete cylinders. A total of 39 plain concrete (30.1 MPa) cylindrical specimens were cast, most confined using one or two layers of Carbon Fiber Reinforced Polymer (CFRP) wraps and tested with inclination angles ranging from 0° to 15°. Results show that increasing the fiber deviation angle from 0° (hoop direction) to 15° reduces the confined strength and ultimate axial strain by approximately 22% and 35%, respectively, for single-layer CFRP-confined specimens, with comparable reductions for two-layer specimens. These findings indicate that the commonly adopted 5° deviation angle limit may lead to about an 8% reduction in confined strength and strain. Furthermore, modification factors are proposed to improve the accuracy of existing confinement models. The results of this study provide engineers with valuable experimental evidence for assessing the confinement efficiency of FRP jackets with small fiber deviations and for refining design predictions in practical applications.

Keywords FRP confined concrete · Fiber orientation · Effective confining pressure · Peak stress · Ultimate strain

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Notation

D	Diameter of concrete specimen (mm).
E_f	Modulus of elasticity of FRP (MPa).
E_c	Modulus of elasticity of unconfined concrete (MPa).
f'_{cc}	Compressive strength of confined concrete (MPa).
f'_{co}	Compressive strength of unconfined concrete (MPa).
F_f	Tensile strength of FRP (MPa).
f_l	Confining pressure provided by FRP wrap (MPa).
H	Height of concrete specimen (mm).
t_f	Total thickness of FRP wrap (mm).
α	Fiber orientation angle with respect to the hoop direction (degrees).
β_1	Fiber angle modification factor for confining pressure used in calculation of strength.
β_2	Fiber angle modification factor for confining pressure used in calculation of ultimate strain.
ϵ_{co}	Peak compressive strain of unconfined concrete (%).
ϵ_{fe}	Effective tensile strain of FRP (%).

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ϵ_{fu} Ultimate tensile strain of FRP (%).
ϵ_{ccu} Ultimate compressive strain of confined concrete (%).
ϵ_{ccul} Ultimate lateral strain of confined concrete under compression (%).

1 Introduction

Due to the aging of infrastructures in the world, the need for reliable and applicable strengthening methods has increased significantly in past decades. Fiber Reinforced Polymers (FRPs) have been introduced as suitable materials for the rehabilitation and retrofitting of damaged and deficient reinforced concrete (RC) structures in recent years (Arabshahi and Tavakkolizadeh 2021; Rostami Aghouy et al. 2025). The rapid growth in the use of FRP materials is owed to its unique characteristics as well as a significant number of studies performed on different aspects of its behavior and application (Arabshahi et al. 2020; Irshidat and Al-Husban 2022; Sengun and Arslan 2022).

Confining concrete columns using FRP wraps significantly improves their strength and ductility. However, this improvement depends on different factors, among which the confining pressure provided by FRP wraps is decisive (ACI 440.2, 2017; Nematzadeh et al. 2021). Confining pressure depends on the geometry, materials properties as well as the orientation of FRP sheets. As reported by fib bulletin-14 (2001), fiber orientation significantly affects the mechanical properties of FRP materials, such that even small deviations in the fiber angle result in a considerable reduction in its confining effects. Accordingly, most current design codes consider this impact on the effectiveness of FRP confinement by limiting the deviation from the intended direction of fiber alignment to 5° (ACI 440.2, 2017). However, no exact reasoning has been provided for the value of this restriction (Banaeipour et al. 2023). Many studies have been performed on FRP applications for the confinement of concrete columns in the past decades (Ziaadiny and Abbasnia 2016; Shayanfar et al. 2022; Fanaradelli and Rousakis 2021). However, the number of studies on the behavior of FRP-confined concrete columns with inclined fibers is limited. In an early study, Mirmiran and Shahawy (1997) performed an experimental investigation on CFFTs with ±15º glass fibers. They reported that their proposed model (suggested for hoop-directed fibers) overestimates the strength of tested specimens. In another study, Rochette and Labossiere (2000) investigated the effect of fiber deviation angles of ±15º on the strength and ductility of small-scale circular, square, and rectangular concrete specimens under axial loading. They observed that despite the reduction in the confinement effectiveness, inclined fiber angles improved the ductility of the confined concrete.

The first large-scale tests on FRP-wrapped RC columns with inclined fiber angles of 45º were conducted by Pessiki et al. (2001). They reported a significant reduction in the confining effectiveness due to fiber deviation. In another study, Hong and Kim (2004) performed full-scale experiments on carbon filament-wound circular and square columns by testing specimens with different fiber angles of ±30º, ±45º, ±60º, and ±90º relative to the column axis. Based on their findings, they proposed strength models by modifying the well-known Richart et al. (1928) model. Considering six different fiber orientations, Li (2006) performed studies on FRP-confined concrete columns and once more proved the inaccuracy of the available models in predicting the strength and strain of confined columns with inclined fibers. Sadeghian et al. (2010) investigated the influence of ±45º fiber angles on the performance of FRP confined concrete under cyclic loading and reported a reduction in the strength and an improvement in the ductility of confined concrete. Another similar experimental study on the FRP confined columns with inclined fiber angles was performed by Piekarczyk et al. (2011). They reported that the specimens confined by ±45º fiber angles provide the highest ductility.

Vincent and Ozbakkaloglu (2013) performed a comprehensive experimental study by testing 24 CFFT and FRP-wrapped circular concrete columns with different fiber angles of 45º, 60º, and 75º relative to the column axis, and reported similar results to previous studies. In another study, Zhang et al. (2020a) examined the performance of circular CFFTs with different fiber orientations of ±45º, ±60º, and ±80º relative to the column axis. They showed that the available models were not able to accurately estimate the peak stress and ultimate strain of FRP-confined concrete with inclined finer angles.

Recent studies have also explored the influence of large fiber deviation angles on the axial behavior of FRP-confined composite columns. Zhang et al. (2019, 2020a, b) conducted monotonic axial compression tests on hybrid FRP–concrete–steel double-skin tubular columns with deviation angles of ±45°, ±60°, and ±80°. Their results consistently indicated that increasing the fiber deviation angle enhances the confinement effect provided by the FRP tube, primarily due to improved shear resistance and hoop stress redistribution; however, it simultaneously reduces the ultimate axial strain of confined concrete, leading to decreased ductility. These findings provide valuable insights into the mechanical behavior of FRP-confined systems at large deviation angles, complementing the current study, which focuses on relatively small fiber angles (up to 15°).

In addition, to these experimental studies, Hain et al. (2019) analytically determined the limit fiber angle for concrete-filled FRP tubes that provide sufficient confining. Based on their analysis, 48.5º relative to the hoop direction is considered the threshold for confinement effectiveness.

The effect of small deviation angles (i.e., less than 15º) has not been studied in any of the previously mentioned studies. Recently, Banaeipour et al. (2023) conducted a thorough numerical study to investigate the effect of small fiber angles on the performance of FRP-confined concrete cylinders to verify the prescribed limiting threshold of 5º by design codes. Based on the attained results from their developed finite element models, they proposed allowable deviation angles for fibers in FRP wraps considering different performance parameters including strength, ultimate strain, and maximum energy dissipation capacity equal to 6º, 3º, and 2º, respectively. These threshold values guarantee a maximum reduction of 2.5% in the respective parameters with a 95% confidence.

Recent research has also highlighted the significant role of fiber orientation in the flexural performance of FRP–concrete–steel composite members. For instance, Zhang et al. (2025) investigated the four-point bending behavior of FRP–concrete–steel tubular beams and reported that inclined fiber orientations, particularly around ±45°, enhanced longitudinal tensile capacity, improved flexural strength, and reduced cracking propagation compared to higher deviation angles. These findings emphasize that fiber orientation not only affects the axial behavior of FRP-confined elements but is also a key parameter in optimizing the flexural performance and durability of composite members.

Table 1 presents a comparative summary of the key parameters, findings, and limitations of the previous studies investigating the effects of fiber deviation angles on FRP-confined concrete columns. This comparison highlights the research gaps, especially the limited experimental data on small fiber deviation angles (< 15°), which justifies the necessity of the present study.

Although the majority of FRP confinement applications rely on hoop-oriented fibers to ensure optimal confinement, investigating the effect of fiber inclination remains important. In some experimental studies, inclined fibers have shown favorable influence on ductility, particularly at large deviation angles. Additionally, in practical situations, minor deviations from the hoop direction may occur unintentionally due to construction limitations or poor workmanship. Moreover, manufacturing techniques such as filament winding may result in small predetermined inclination angles. Therefore, studying the role of fiber orientation can contribute to a better understanding of the actual behavior and reliability of FRP-confined concrete elements under various conditions. Based on the presented literature review, some

Table 1 Comparative summary of previous studies on FRP-confined concrete columns with inclined fibers

Reference	Specimen Type & Scale	Fiber Orientation (°)	Key Findings	Shortcomings / Gaps
Mirmiran and Shahawy (1997)	CFFTs, small-scale	±15	Model for hoop fibers overestimates strength of inclined-fiber specimens	Limited to small fiber angles; no strain/ductility evaluation
Rochette and Labossiere (2000)	Circular, square & rectangular specimens, small-scale	±15	Reduced confinement effectiveness; improved ductility	Small-scale; only one deviation angle (±15°)
Pessiki et al. (2001)	RC columns, large-scale	45	Significant reduction in confining effectiveness	Single deviation angle; no strain model
Hong and Kim (2004)	Carbon filament-wound columns, full-scale	±30, ±45, ±60, ±90	Proposed modified Richart-based model	Focused on large angles; no discussion for small angles
Li (2006)	FRP-confined columns	6 orientations (not specified)	Existing models inaccurate for inclined fibers	No practical recommendations for small angles
Sadeghian et al. (2010)	FRP-confined concrete, cyclic loading	±45	Reduced strength, improved ductility	Focused only on cyclic loading; no small angles
Piekarczyk et al. (2011)	FRP-confined columns	±45	Highest ductility observed	Single angle; no strength model modification
Vincent and Ozbakkaloglu (2013)	CFFT & FRP-wrapped columns	45, 60, 75	Similar trends to previous studies; ductility increases with higher angles	Focused on medium–large angles; no low-angle data
Zhang et al. (2020a)	Circular CFFTs	±45, ±60, ±80	Models inaccurate for peak stress & strain	No small-angle investigation
Zhang et al. (2019, 2020a, b)	Hybrid FRP–concrete–steel tubular columns	±45, ±60, ±80	Higher angles improve confinement via shear redistribution but reduce ductility	Focus on composite systems; large angles only
Hain et al. (2019)	Analytical, concrete-filled FRP tubes	~48.5 (threshold)	Defined limit angle for effective confinement	Purely analytical; no experimental small-angle validation
Banaeipour et al. (2023)	Numerical simulation of FRP-confined cylinders	< 15 (2, 3, 6 thresholds)	Proposed allowable deviation angles ensuring < 2.5% reduction in key parameters	No experimental validation; purely numerical

Table 2 Chemical composition of the utilized cement provided by manufacturer

Chemical composition	Test Results	ISIRI standard 389 (1996)
SiO_2 (% by weight)	22.10	>20
Al_2O_3 (% by weight)	5.20	>6
Fe_2O_3 (% by weight)	3.55	<6
CaO (% by weight)	65.10	62–66
MgO (% by weight)	2.10	<5
SO_3 (% by weight)	2.25	<3
K_2O (% by weight)	0.72	0.5-1
Na_2O (% by weight)	0.36	0.2–0.4
Free CaO (% by weight)	1.15	-
Blaine (cm^2/gr)	3012	-

Table 3 Properties of utilized aggregates

Material	Properties	Unit	Value
Coarse aggregate	Apparent density	kg/m^3	1560.2
	Moisture content	%	0.18
	Water absorption	%	0.52
Fine aggregate	Apparent density	kg/m^3	1705.2
	Moisture content	%	0.42
	Water absorption	%	0.75
	Fineness modulus (F.M)	-	2.75
	Sand equivalent (S.E)	%	80

research gaps are identified. First, there is very limited (if not at all) experimental data available on the performance of FRP-confined concrete columns with small fiber inclinations of less than 15º. Second, if the existing deviation angle is beyond the prescribed limit defined by design codes or other published studies, existing models for confined concrete are not able to provide an accurate estimation of the behavior in such cases. Therefore, the main objectives of the present study were to provide necessary experimental results to shed light on the performance of FRP-confined concrete cylinders with small deviations in their fiber orientation. For this purpose, 36 CFRP confined and 3 unconfined concrete specimens with different fiber orientations of 0º, 3º, 5º, 8º, 10º, and 15º were prepared and tested under concentric monotonic compression loading. In addition, modification factors are proposed based on the attained experimental results to make the available design-oriented models applicable for the prediction of strength and ultimate strain of FRP-confined concrete cylinders with fiber orientations of less than 15º.

The manuscript is organized in the following order: Sect. 2 explains the details of the performed experimental program. The attained results are presented in Sect. 3, followed by a discussion on the attained results in Sect. 4. Modification factors to include the effect of small deviation angles in the existing predictive models are presented in Sect. 5. Finally, the concluding remarks are given in Sect. 6.

2 Experimental program

Details of the performed experimental program including materials used, specimen preparation, naming convention, and the test setup are presented in this section.

2.1 Materials

The properties of the material used in this experimental program are as follows.

Cement: Standard Type II Portland cement was used for making the concrete mix. Table 2 presents the chemical composition of the used Portland cement.

Aggregates: Fine and coarse aggregates with suitable fineness and gradation were used. The properties of the coarse and fine aggregates were determined according to ASTM standards. ASTM C127(2024) was used for coarse aggregate apparent density, moisture content, and water absorption. The apparent density, moisture content, and water absorption of fine aggregates was determined following ASTM C128 (2022). Finally, the fineness modulus and the sand equivalent were determined according to ASTM C136 (2019) and ASTM D2419 (2022), respectively. Table 3 gives the properties of used aggregates:

CFRP: CFRP sheets were made of unidirectional carbon fabrics and a two-part epoxy resin using the wet layup technique as shown in Fig. 1. Therefore, the same epoxy resin was used to bond CFRP sheets to concrete cylinders. The mechanical properties of the unidirectional carbon fabric used are presented in Table 4 based on the manufacturer's data sheet. Table 5 also presents the properties of used epoxy resin.

Concrete: The mix proportions of the utilized concrete are presented in Table 6. The concrete mix had density of 2380 kg/m^3 and the slump of 140 mm using a locally produced plasticizer.

2.2 Specimen preparation

A total of 36 CFRP-confined and 3 unconfined concrete cylinders concrete were prepared. The effect of fiber orientation on the performance of confined concrete columns was investigated by wrapping one and two layers of unidirectional CFRP sheets with angles of 0º, 3º, 5º, 8º, 10º, and 15º relative to the hoop direction (perpendicular to specimen longitudinal axis) using wet lay-up method. Concrete cylinders were 200 mm in diameter (D) and 600 mm in height (H). The utilized name convention in this study was as follows: Lx-Ax. Here, x stands for a quantity. The first number after the letter the letter L stands for the number of confining FRP layers and second number after the letter A stands for the fiber orientation angle. For instance, a specimen

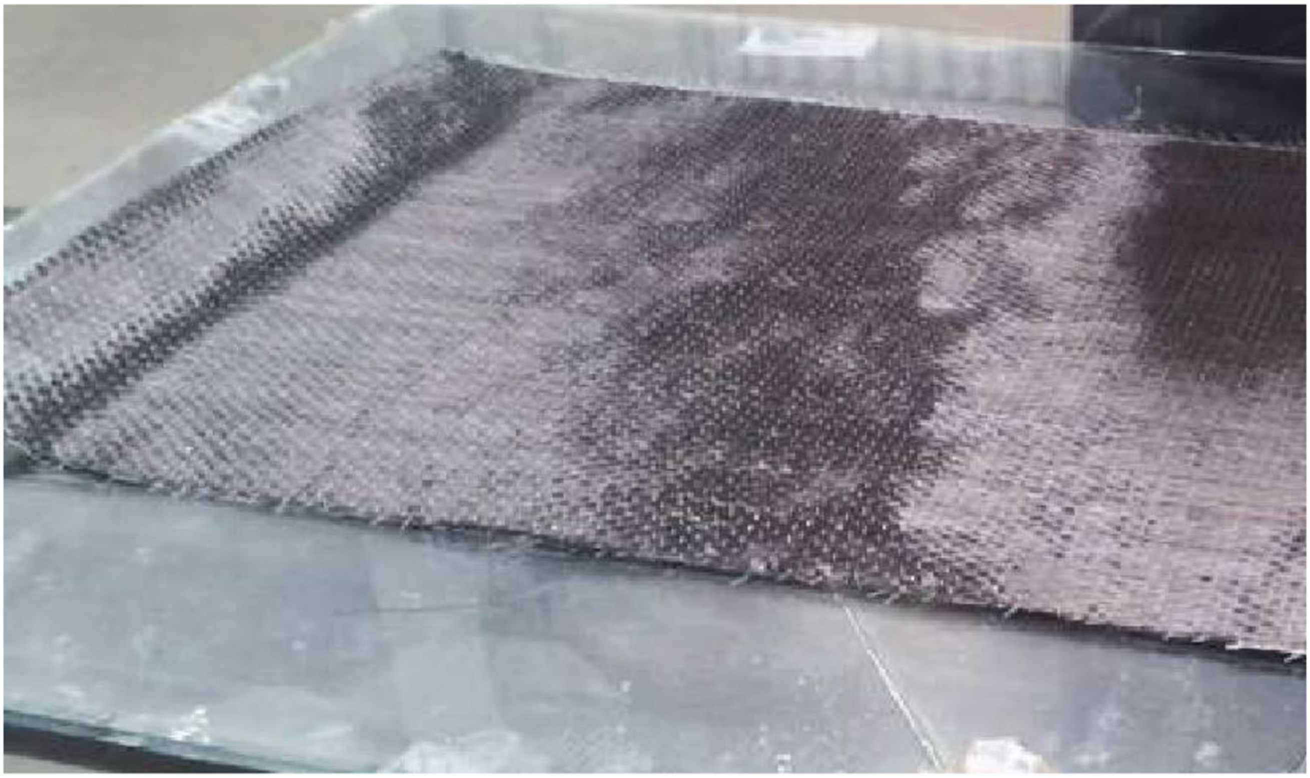

Fig. 1 Unidirectional carbon fabrics used in this study

Table 4 Properties of the carbon fabric used in the study provided by manufacturer

Properties	Carbon fabric
Modulus of Elasticity (GPa)	230
Tensile strength (MPa)	3450
Ultimate strain (%)	1.50
Thickness (mm)	0.11
Mass of unit area (kg/m^2)	0.20

Table 5 Properties of the epoxy resin used in the study provided by manufacturer

Properties	Epoxy Resin
Modulus of elasticity (GPa)	2.50
Tensile strength (MPa)	55
Ultimate strain (%)	2.60
Density (kg/m^3)	1.15

Table 6 Mix proportions for 1 m^3 concrete the specified target compressive strength

Concrete Constituent	Value
Cement (kg)	451
Water (kg)	204
Coarse aggregates (kg)	1069
Fine aggregates (kg)	640
Water to cement ratio	0.45
Plasticizer (% of Cement)	1.0

Table 7 Details of confining wraps of test specimens

Name	CFRP layers	Orientation angle (degrees)
L0 (Ref)	0	-
L1-A0	1	0
L2-A0	2	0
L1-A3	1	3
L2-A3	2	± 3
L1-A5	1	5
L2-A5	2	± 5
L1-A8	1	8
L2-A8	2	± 8
L1-A10	1	10
L2-A10	2	± 10
L1-A15	1	15
L2-A15	2	± 15

Note: Three specimens for each series were prepared and tested

named L2-A10 is confined by two layers of CFRP wraps with a fiber orientation angle of 10º. The details of confining wraps of the tested specimens are given in Table 7. "±" sign preceding the angle value indicates that the specimen was reinforced with two layers of FRP sheets applied at opposite inclination angles, resulting in a cross-orientation (e.g., +45°/–45°) between the layers.

Concrete cylinders were cast and removed from the molds after 24 h and cured in a saturated lime water for 27 more days as shown in Fig. 2. Then, depending on the confining configurations of each series, one or two layers of CFRP sheets with different fiber orientation were wrapped around the concrete cylinders. A thin layer of epoxy resin was applied to the concrete surface first and then carbon fabrics wrapped around the cylinders with desired orientation with 150 mm overlaps and air bubbles were removed by applying hand rollers with uniform pressure. To achieve the desired small fiber deviation angles (0°, 3°, 5°, 10°, and 15°), reference lines were marked on the surface of the specimens using a protractor before wrapping. The FRP sheets were carefully aligned with these lines during application, and their orientation was frequently checked and adjusted until the epoxy resin cured. This procedure allowed maintaining the deviation angles within an approximate tolerance of less than ± 1°. Finally, both ends of specimens were additionally confined using 2 horizontal layers of 100 mm wide CFRP sheet to prevent undesired failures during loading. Figure 3 demonstrates the schematic of confining details, and a sample confined specimen.

2.3 Test setup

The confined specimens were cured and ready to be tested after 10 days. The concentric axial compression was applied to the specimens using a 2500 kN hydraulic jack as shown in Fig. 4a. The displacement control loading protocol with a loading rate of 1 mm/min was used to ensure quasi-static loading conditions and to allow for accurate observation of the stress–strain response, particularly in the post-peak region (Hain et al. 2019; Nematzadeh et al. 2021). Figure 4b demonstrates the test setup. The applied load to the specimens was recorded using a 2000 kN capacity load cell with an accuracy of 100 N. The axial and lateral deformations of the specimens were measured using two Linear Variable Differential Transducers (LVDTs) with a displacement range of 5 mm and an accuracy of 0.005 mm. One LVDT was placed vertically along the loading axis to record axial shortening, while the other was installed horizontally at mid-height of the specimen to capture lateral expansion during loading, as shown in Fig. 4b. The values of loads and deformations were recorded by a real-time data logger to calculate values of stresses and strains, to display during testing and to save for future analysis.

3 Test results

The attained experimental results, including peak stress and ultimate strain, stress-strain curves and failure modes are presented in this section.

3.1 Strengths and ultimate strains

The recorded average values for the confined concrete strength, f'_{cc}, and ultimate axial strain, ϵ_{ccu}, and ultimate lateral strain, ϵ_{ccul}, of the tested specimens are reported in Table 8. It must be noted that the average values of the strength and ultimate axial strain of three unconfined concrete cylinders, f'_{co} and ϵ_{co}, were also determined as 30.1 MPa and 0.25%, accordingly.

Fig. 2 Cured concrete cylinders

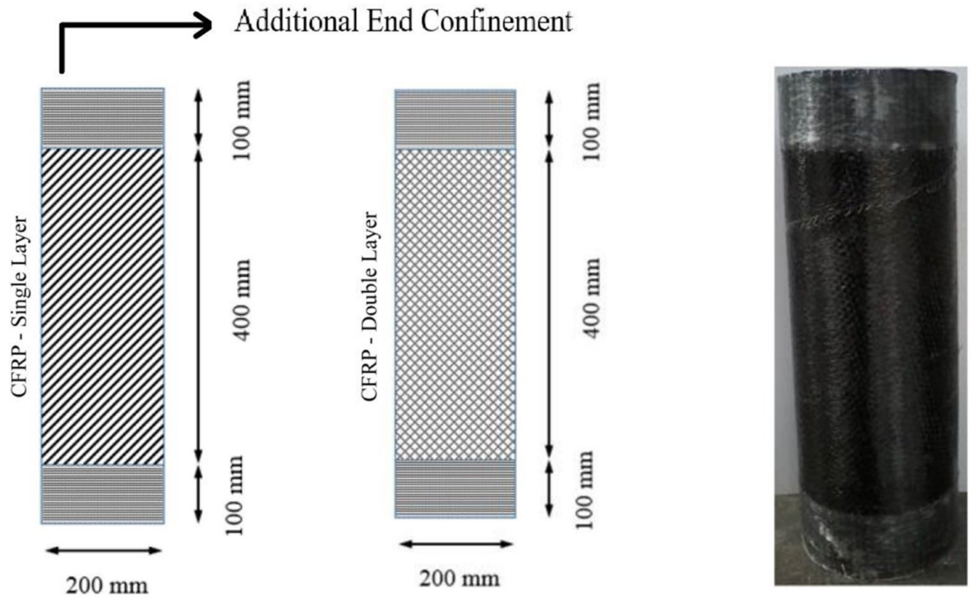

Fig. 3 CFRP confined concrete cylinders, (**a**) Schematic view of column confined with single inclined layer (**b**) Schematic view of column confined with double inclined layers (**c**) CFRP confined cylinder

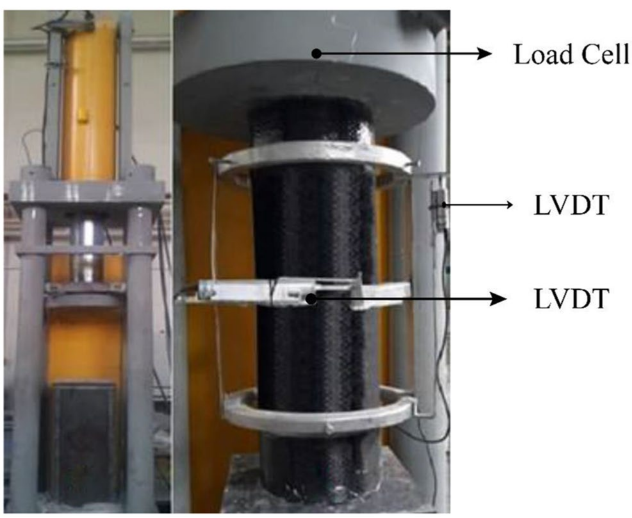

Fig. 4 Test setup, (**a**) Hydraulic jack (**b**) Specimen with mounted extensometer

3.2 Stress-strain behaviors

The stress-strain curves of the specimens are also depicted in Figs. 5 and 6.

The clear trend is that deviation of the fiber from the circumferential direction (zero orientation angle) reduces both the peak confined stress and the ultimate axial strain of confined specimens. The variation trend of the ultimate lateral strain with the orientation angle is similar to that of axial strain, confirming that increasing the fiber orientation angle decreases the overall confinement efficiency. Moreover, specimens with two CFRP layers consistently exhibited higher peak confined stresses and larger ultimate axial and lateral strains compared to those with a single layer, indicating improved confinement effectiveness and ductility due to the increased thickness of the FRP wrap. However, the beneficial effect of using two layers diminished slightly as the fiber deviation angle increased, highlighting the critical role of fiber orientation in fully mobilizing the confinement potential of additional CFRP layers.

3.3 Failure modes

Figure 7 demonstrates failure modes for of the examples of tested specimens. All specimens displayed a sudden brittle failure due to CFRP rupture as apparent in Figs. 5 and 6. Since in the previous studies it was reported that confined specimens with low fiber orientation angle behave in a manner similar to those confined by CFRP wraps with hoop-directed fibers (Vincent and Ozbakkaloglu 2013), such behavior was expected. It is also observed that the specimen ends confined by additional FRP layers, to prevent premature failure, accomplished their intended task successfully and the failure of FRP wraps occurred in the middle height of all tested specimens.

4 Discussion

In this section, a short discussion of the attained experimental results is presented, considering the observed effects of small fiber angle of the peak stress, ultimate strain, and ductility of confined concrete columns.

Table 8 Peak stress and ultimate strains of tested specimens

Name	f'_{cc}(MPa)			ϵ_{ccu} (%)			ϵ_{ccul} (%)			f'_{cc}/f'_{co}	$\epsilon_{ccu}/\epsilon_{co}$
	Value	Mean	CoV (%)	Value	Mean	CoV (%)	Value	Mean	CoV (%)		
Control specimens (Unconfined)	30.8	30.1	2	0.26	0.25	6	0.13	0.13	4	1.00	1.00
	29.6			0.23			0.13				
	29.9			0.25			0.14				
L1-A0	42.30	41.0	3	1.35	1.32	3	0.72	0.72	2	1.36	5.28
	40.90			1.28			0.71				
	39.30			1.32			0.74				
L2-A0	51.50	53.5	5	2.15	2.34	9	1.22	1.23	2	1.78	9.36
	52.40			2.57			1.26				
	56.50			2.31			1.21				
L1-A3	40.50	40.1	3	1.24	1.25	4	0.73	0.70	4	1.33	5.00
	41.20			1.31			0.68				
	38.50			1.21			0.71				
L2-A3	50.50	52.1	3	2.13	2.17	2	1.27	1.20	7	1.73	8.68
	52.20			2.21			1.11				
	53.50			2.18			1.21				
L1-A5	38.70	39.0	4	1.24	1.21	3	0.65	0.68	4	1.30	4.84
	40.50			1.22			0.71				
	37.80			1.18			0.67				
L2-A5	48.50	49.9	3	2.07	2.11	2	1.12	1.05	7	1.66	8.40
	50.10			2.12			1.07				
	51.00			2.13			0.98				
L1-A8	35.80	37.4	5	1.13	1.15	5	0.68	0.67	6	1.24	4.60
	39.30			1.10			0.63				
	37.20			1.21			0.71				
L2-A8	49.20	47.5	4	1.98	1.95	8	1.03	1.05	3	1.58	7.80
	45.40			1.78			0.98				
	47.80			2.10			1.05				
L1-A10	37.40	35.2	7	1.10	1.02	7	0.68	0.65	5	1.17	4.08
	35.60			0.98			0.62				
	32.50			0.97			0.64				
L2-A10	43.70	43.7	2	1.61	1.65	4	1.03	1.00	4	1.45	6.60
	42.80			1.63			0.95				
	44.60			1.72			1.02				
L1-A15	35.20	32.2	8	0.90	0.86	5	0.63	0.61	3	1.07	3.44
	30.50			0.86			0.62				
	31.00			0.81			0.60				
L2-A15	37.80	39.7	5	1.43	1.42	5	1.02	0.95	7	1.32	5.68
	39.80			1.49			0.88				
	41.50			1.35			0.94				

4.1 Effects of fiber deviation angle on strength and ultimate strain

The variation of strength and ultimate strain enhancement due to FRP confinement relative to unconfined specimens is illustrated in Fig. 8, while Fig. 9 demonstrates the reduction of confinement effectiveness with increasing fiber deviation angles from the hoop direction.

The maximum enhancement in both peak stress and ultimate axial strain occurs when fibers are aligned in the hoop direction, whereas increasing the deviation angle reduces both values. This behavior can be explained by the fact that the hoop-oriented fibers are primarily responsible for resisting lateral dilation of the concrete core, effectively transforming tensile stresses in the FRP into lateral confining pressure. When the fibers are inclined, a portion of the tensile stress is redirected along the longitudinal axis, thereby reducing the effective hoop stress and confinement pressure. Consequently, the ultimate strain, which is highly sensitive to lateral dilation, shows a sharper reduction than the peak confined stress. This observation aligns with the findings of Baneipour et al. (2023), who recommended a stricter allowable deviation angle for ultimate strain (3°) compared to peak stress (6°). Based on the present results,

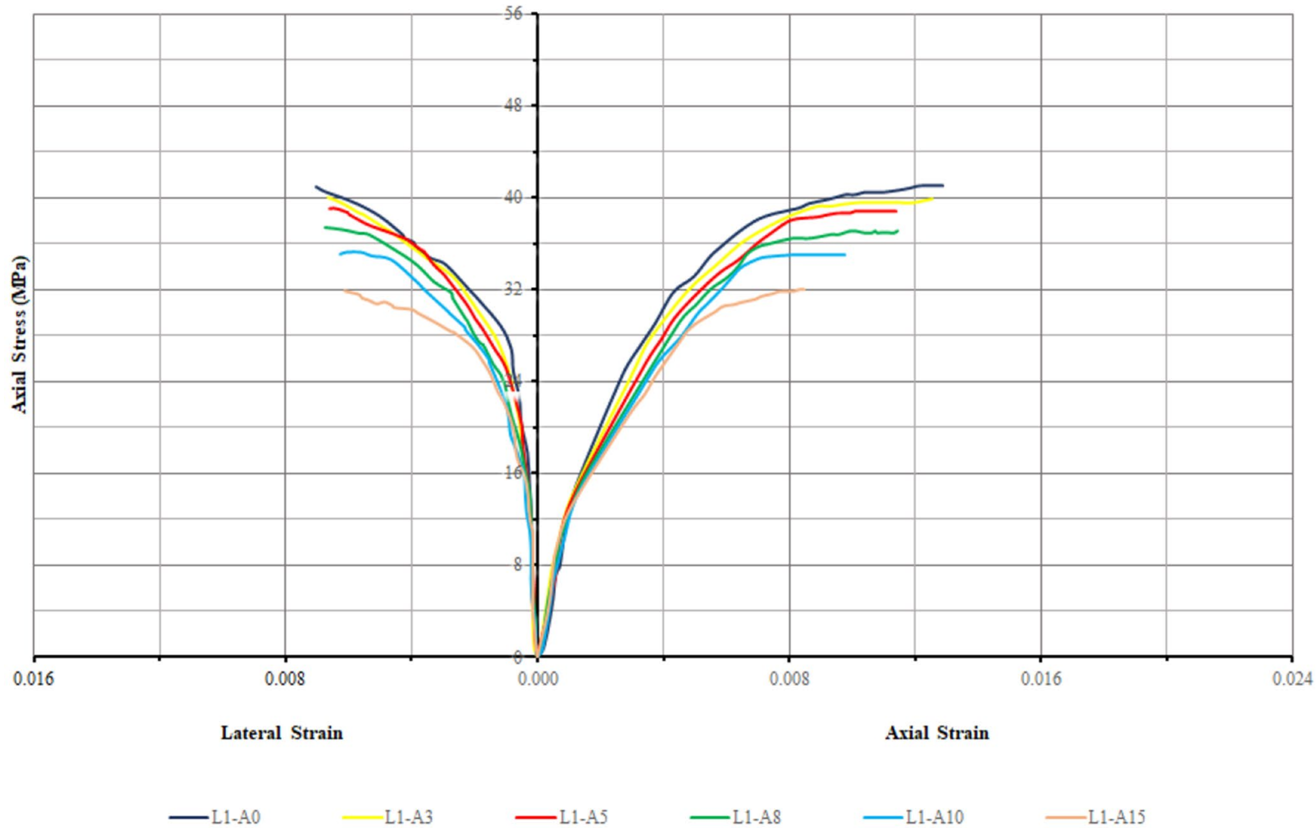

Fig. 5 Axial stress vs. axial and lateral strains for confined specimens with one layer of CFRP

the code-prescribed limiting deviation angle of 5° leads to a maximum 8% reduction in both confined strength and strain relative to perfectly hoop-directed fibers, which may still be acceptable in practical applications.

4.2 Effects of number of confining layers

The number of CFRP confining layers significantly affects the mobilization of lateral confinement pressure. Increasing the number of layers increases the hoop stiffness and tensile capacity of the FRP jacket, resulting in higher confinement pressure and, consequently, greater strength and strain enhancement. However, the influence is more pronounced for the ultimate strain than for the peak stress, as the additional layers delay the onset of hoop rupture and allow greater lateral expansion before failure. As shown in Fig. 9, the addition of a second layer approximately doubles the ultimate strain enhancement relative to the unconfined state.

4.3 Effect of fiber deviation on ductility

Based on previous studies (Piekarczyk et al. 2011; Sadeghian et al. 2010), large inclination angles (>30°) have been associated with increased ductility due to reduced confinement efficiency and a more gradual second branch of the stress–strain curve. However, such behavior was not observed in this study, as the small deviation angles investigated (≤15°) were insufficient to trigger significant redistribution of stresses or a ductile failure mode. Instead, the reduced confinement efficiency at small deviation angles predominantly resulted in lower strength and strain capacity rather than enhanced ductility.

5 Modification factor

As mentioned previously, the earlier studies showed that the predicting models for FRP-confined concrete overestimate the strength and ultimate strain of FRP-confined columns with inclined fibers. It is obvious that fiber angles affect the FRP wrap properties and as derived by Hain et al. (2019), this affects the confining pressure provided by FRP wrap. Therefore, it seems logical to modify the confining pressure to achieve more accurate predictions from the available models (Gharaei-Moghaddam et al. 2023). The confining pressure, usually designated by f_l, is defined as follows:

$$f_l = \frac{2F_f t_f}{D} \tag{1}$$

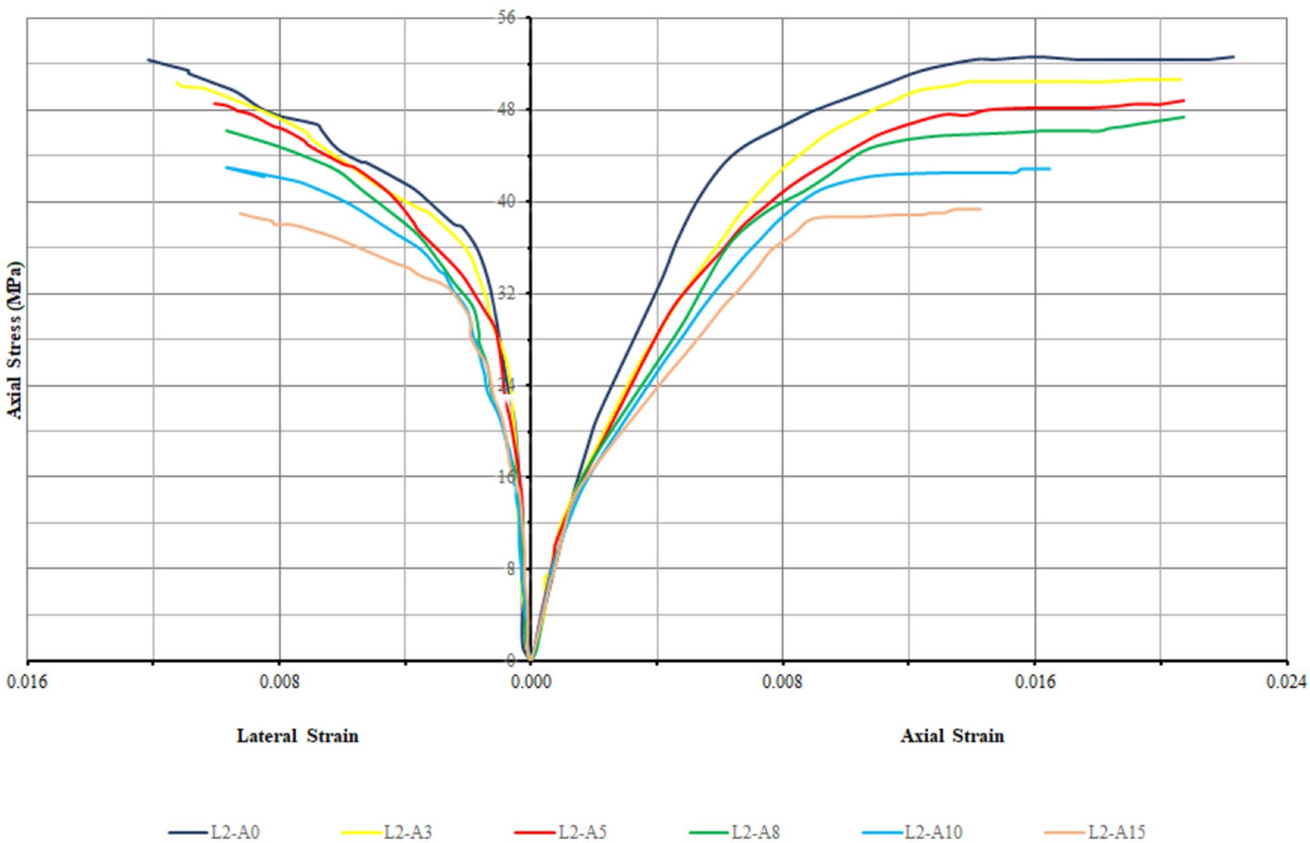

Fig. 6 Axial stress vs. axial and lateral strains for confined specimens with two layers of CFRP

In which, D is the column diameter, and F_f and t_f stand for the tensile strength and the total thickness of FRP wraps, respectively.

Accordingly, it is assumed that if a modified confining pressure $f_l^* = \beta f_l$ is used in the existing models for the strength and ultimate strain of FRP confined columns, the prediction should have higher accuracy. Based on this assumption, and performing nonlinear regression using the attained experimental results, simple modification factors, β , are determined for strength and ultimate strain. For this purpose, the subsequent relations proposed by Arabshahi et al. (2020) are used as the base model:

$$f'_{cc} = f'_{co} + \frac{39 f_l}{\ln^2 (f'_{co})} \tag{2}$$

$$\epsilon_{cu} = \frac{0.21 {f_l}^{0.68}}{f'_{co} - \ln (\epsilon_{co})} \tag{3}$$

where, f'_{cc} and f'_{co} are the confined and unconfined concrete strength, respectively. ϵ_{cu} stands for the ultimate strain of confined concrete and ϵ_{co} designates the ultimate strain of unconfined concrete. Based on the above-mentioned idea, replacing the existing confining pressure with the modified one leads to the following equations:

$$f'_{cc} = f'_{co} + \frac{39 \beta_1 f_l}{\ln^2 (f'_{co})} \tag{4}$$

$$\epsilon_{cu} = \frac{0.21 (\beta_2 f_l)^{0.68}}{f'_{co} - \ln (\epsilon_{co})} \tag{5}$$

here, β_1 and β_2 are the modification factors for strength and ultimate strain, respectively.

By using the experimental data and solving Eqs. (4) and (5) for β_1 and β_2, respectively, the values of these modification factors for each specimen are derived. It is assumed that these factors are only functions of fiber angles, α (in degrees). Performing regression using the obtained values for the modification factors as dependent variables and fiber angle as the independent variable, the following equations are derived:

$$\beta_1 = 1 - 0.033\alpha \tag{6}$$

$$\beta_2 = 1 - 0.046\alpha \tag{7}$$

Fig. 7 Failure modes of tested specimens

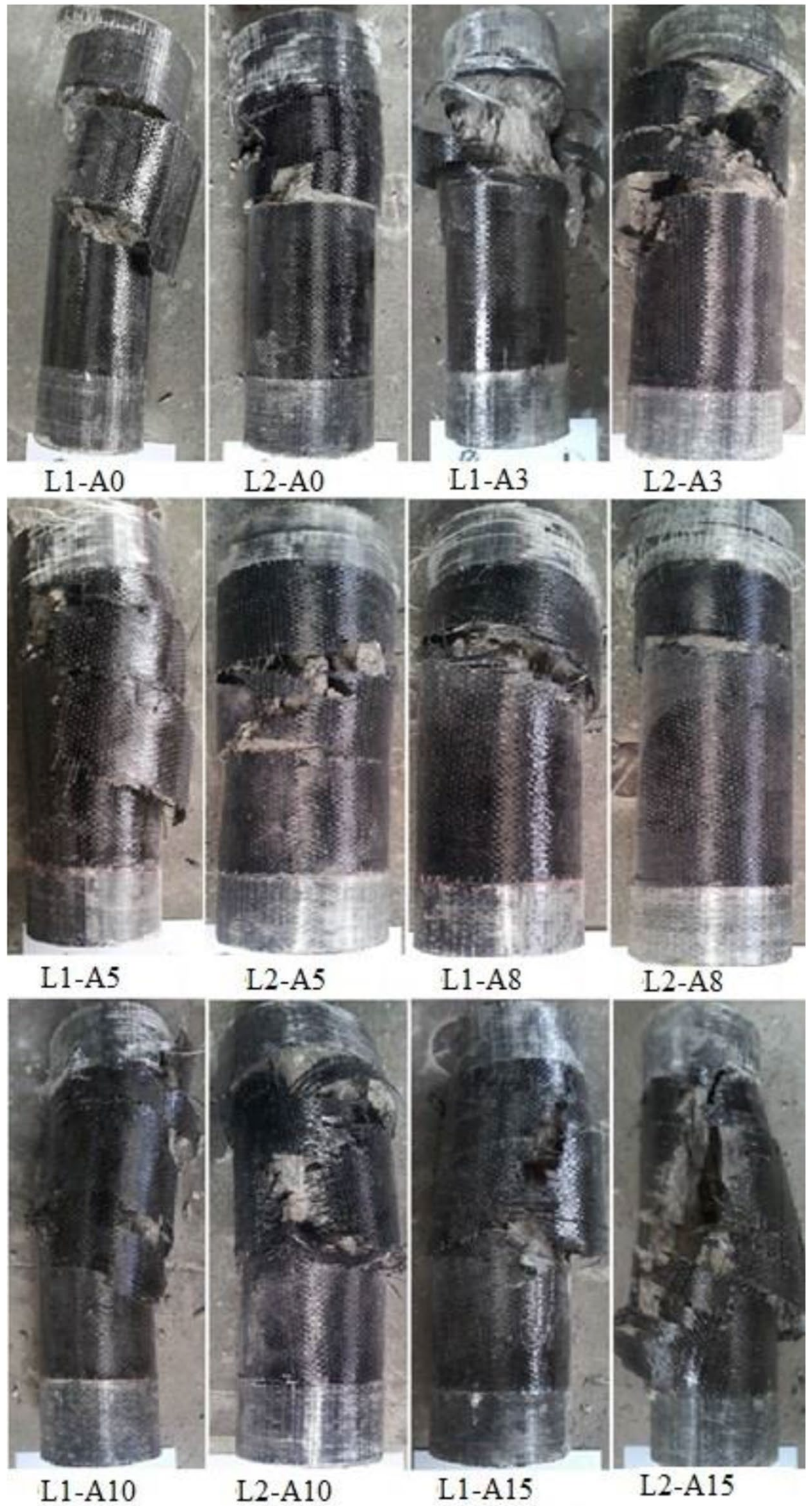

Table 9 compares the accuracy of the predictions made by Eq. (2) Eq. (3) with and without the application of the modification factors. It is evident that the application of the derived modification factors improves the accuracy of the predicted values by the utilized models, especially for the confined ultimate strain. It is noteworthy that since these factors are applied to the confining pressure, they could be used for other predictive models as well.

To verify that the proposed modification factors for the ultimate strain of confined columns with inclined fiber angles are also applicable to other existing predictive models, these factors were applied to the well-known confinement model

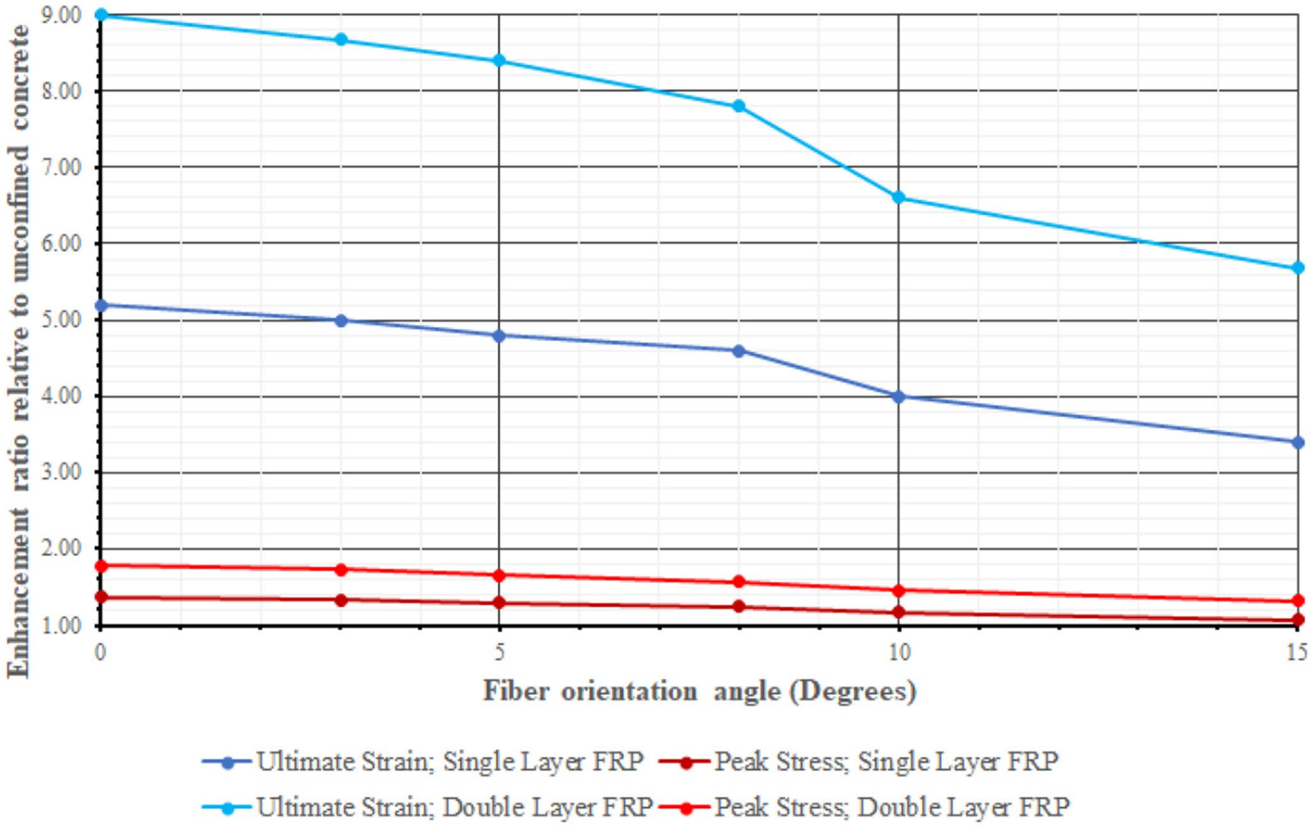

Fig. 8 Variations of confined strength and ultimate strain with the angles

proposed by Spoelstra and Monti (1999), expressed as follows:

$$f'_{cc} = f'_{co}\left(0.2 + 3\left(\frac{f_l}{f'_{co}}\right)^{0.5}\right) \tag{9}$$

$$\epsilon_{cu} = \epsilon_{co}\left(2 + 1.25\frac{E_c}{f'_{co}}\left(\frac{f_l}{f'_{co}}\right)^{0.5}\left(0.0117 + 0.0321\left(\frac{2E_f t_f}{DE_c}\right)\right)\right) \tag{9}$$

where, E_c is the modulus of elasticity of unconfined concrete, determined as:

$$E_c = 4700 {f'_{co}}^{0.5} \tag{10}$$

The comparison between the original and modified predictions of this model is presented in Table 10. The results clearly indicate that incorporating the proposed modification factors yields significantly improved predictions, confirming their applicability to other predictive models as well.

6 Conclusion

In the present study, a series of concrete cylinders confined by CFRP wraps with inclined fiber angles were tested under monotonic axial compression to investigate the effect of fiber angles lower than 15º related to the hoop direction. In addition, using the attained experimental results, modification factors are proposed to modify available models for FRP confined concretes with inclined fibers. The most important conclusions drawn from this study are:

- The experimental results showed that an increase in the fiber orientation angle from 0º (hoop direction) to 15º reduced both strength and ultimate strain of one-layer FRP-confined concrete by about 22% and 35%, respectively. These reducing effects are about 26% and 37% for two-layer FRP-confined concrete.
- Variation of the lateral ultimate strain of confined concrete also showed a similar trend. Increasing the fiber orientation angle from 0º to 15º was accompanied by a 15% reduction of the lateral ultimate strain of one-layer FRP confined concrete, while this reduction is about 23%.

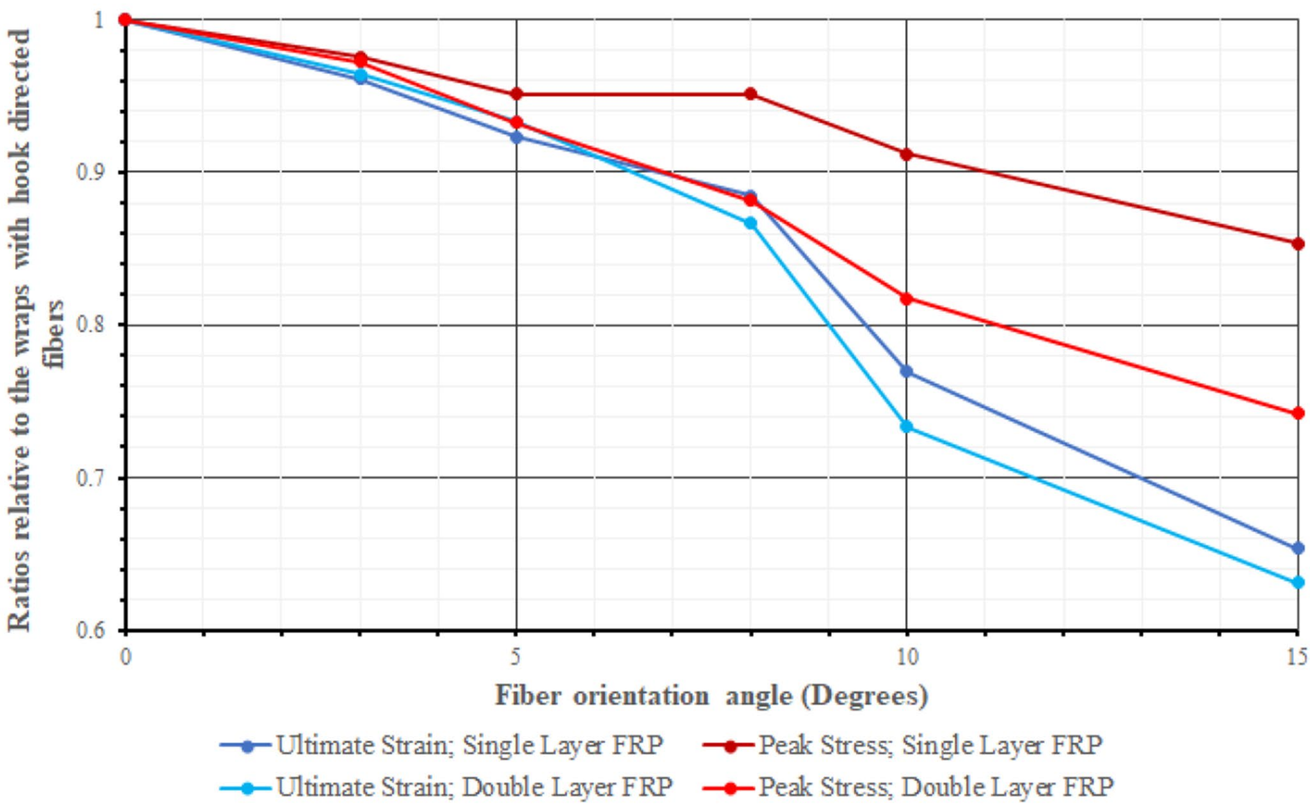

Fig. 9 Normalized values of strength and ultimate strain of specimen respect to control specimen

Table 9 Evaluation of the predicted values for the confined behavior using the original and modified Arabshahi et al. (2020) model

Specimen	Fiber angle (degrees)	β_1	β_2	Ratio of predicted to experimental values			
				Confined strength		Ultimate strain	
				Original	Codified	Original	Modified
L1-A0	0	1	1	1.05	1.05	1.09	1.09
L2-A0	0	1	1	1.04	1.04	0.99	0.99
L1-A3	3	0.90	0.86	1.07	1.04	1.15	1.04
L2-A3	3	0.90	0.86	1.07	1.02	1.06	0.96
L1-A5	5	0.84	0.77	1.10	1.05	1.19	1.00
L2-A5	5	0.84	0.77	1.11	1.03	1.09	0.92
L1-A8	8	0.74	0.63	1.15	1.06	1.25	0.92
L2-A8	8	0.74	0.63	1.17	1.03	1.18	0.87
L1-A10	10	0.67	0.54	1.22	1.10	1.41	0.93
L2-A10	10	0.67	0.54	1.27	1.08	1.40	0.92
L1-A15	15	0.51	0.31	1.33	1.14	1.68	0.76
L2-A15	15	0.51	0.31	1.40	1.08	1.63	0.73
Average				1.16	1.06	1.26	0.93

- It is found that the ultimate strain of confined concrete is more sensitive to the fiber inclination compared to the strength.
- It is shown experimentally, that the proposed limitation angle of 5 degrees by design codes results in a maximum 8% reduction in the confined strength and strain.
- The range of variations of the fiber angle between 0º and 15º was selected because most previous studies considered inclination angles of larger than 15º. Using the attained experimental data and nonlinear regression, modification factors for the confining pressure of FRP wraps with small inclination angles are as follows:

$\beta_1 = 1 - 0.033\alpha$ for Confined Strength.

$\beta_2 = 1 - 0.046\alpha$ for Confined Ultimate strength

Using the proposed factors considerably improves the accuracy of the models to predict the confined strength and ultimate strain of concrete cylinders.

Table 10 Evaluation of the predicted values for the confined behavior using the original and modified Spoelstra and monti (1999) model

Specimen	Fiber angle (degrees)	β_1	β_2	Ratio of predicted to experimental values			
				Confined strength		Ultimate strain	
				Original	Codified	Original	Modified
L1-A0	0	1	1	0.93	0.93	1.25	1.25
L2-A0	0	1	1	0.96	0.96	0.93	0.93
L1-A3	3	0.90	0.86	0.95	0.91	1.32	1.26
L2-A3	3	0.90	0.86	0.99	0.94	1.00	0.95
L1-A5	5	0.84	0.77	0.98	0.91	1.37	1.25
L2-A5	5	0.84	0.77	1.03	0.95	1.03	0.93
L1-A8	8	0.74	0.63	1.02	0.90	1.44	1.23
L2-A8	8	0.74	0.63	1.08	0.95	1.12	0.94
L1-A10	10	0.67	0.54	1.08	0.92	1.62	1.32
L2-A10	10	0.67	0.54	1.18	0.99	1.32	1.05
L1-A15	15	0.51	0.31	1.18	0.89	1.92	1.33
L2-A15	15	0.51	0.31	1.29	0.96	1.53	1.01
Average				1.06	0.93	1.32	1.12

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Declarations

Competing interests The authors declare no competing interests.

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