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Research Article

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Influence of corner radius on the axial compressive behavior of FRP-confined rectangular reinforced concrete columns

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Highlights

- Corner radius significantly affects FRP confinement efficiency.
- Larger corner radii enhance strength and ductility in RC columns.
- Stress concentration at sharp corners lowers confinement efficiency.
- Higher aspect ratios reduce the impact of corner radius on strength.
- FRP confinement is most effective in square sections with rounded edges.
- Sharp corners limit FRP confinement effectiveness

Abstract

The corner radius significantly influences the axial compressive behavior of rectangular reinforced concrete columns externally confined with FRP jackets along their lengths. Fiber reinforced polymer sheets are among the most efficient techniques for enhancing both the strength and ductility of reinforced concrete columns; however, their effectiveness depends on the geometry and edge sharpness. Sharp corners increase stress concentrations and reduce the effective confinement area. This paper analytically investigates the structural behavior of rectangular columns confined with fiber reinforced polymer jackets that experience non-uniform stress distributions at the corners under axial compression. A series of rectangular reinforced concrete columns with varying corner radii were analyzed using reliable analytical models to evaluate the effects on the effective confinement factor, stress-strain response, and axial load capacity. The results reveal that edge sharpness significantly affects the axial compressive behavior of confined rectangular columns. Sections with smaller corner radii behave similarly to unconfined columns and exhibit limited effectiveness from fiber reinforced polymer confinement. Finally, the study concludes that the corner radius is directly proportional to the enhancement of strength and ductility in confined rectangular reinforced concrete columns, playing a critical role in their axial load-carrying capacity.

Keywords: Corner radius; CFRP sheets; RC columns; strength; ductility; confinement; axial behavior

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1. Introduction

Reinforced concrete (RC) columns are the most critical components in structural engineering, as they support axial compression loads, with or without flexural moments. However, these columns often experience deterioration due to various factors, such as seismic events, aging, environmental influences, and increasing loading demands, necessitating effective retrofitting and strengthening methods. The application of fiber-reinforced polymer (FRP) confinement has emerged as an effective technique for enhancing both the load-carrying capacity and ductility of existing RC columns over the past three decades [1–3]. The effectiveness of FRP sheets varies depending on the geometry of the columns. FRP is more effective for circular sections, where uniform stress distribution along the section enhances performance [4]. For rectangular columns, the effectiveness depends on parameters such as the aspect ratio and corner radius. The corner radius plays a crucial role in the confinement mechanism, as sharp corners in rectangular or square cross-sections result in stress concentrations, reducing the efficiency of FRP confinement in improving the structural behavior of columns. Additionally, the maximum confinement stress in rectangular sections typically occurs at the corners [5, 6].

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Several experimental and analytical studies have evaluated the influence of corner radius on the structural behavior of fully CFRP-wrapped rectangular and square RC columns under pure axial compressive loads. Wang and Wu [6] conducted a series of experimental tests on 108 CFRP-wrapped square short RC columns. Their experiments, which involved various corner radii, revealed that the corner radius is directly proportional to the increase in axial compressive capacity. They found that sharp corners have little effect on the enhancement of column strength but significantly contribute to an increase in ductility. Al-Salloum [7] studied the influence of edge sharpness on the compressive behavior of square concrete columns retrofitted with FRP, both experimentally and analytically. Based on his findings, the flattening of the edges of square cross-sections plays a crucial role in delaying the failure of the composite. Furthermore, the effectiveness of FRP has a direct relationship with the corner radius.

Jiang et al.[5] introduced a new methodology to analyze the influence of FRP sheet confinement in square RC columns. They conducted numerous experimental tests and presented a new perspective on the efficiency of FRP jackets. Wei and Wu [8] evaluated the effect of cross-sectional aspect ratio on the structural behavior of rectangular RC columns strengthened with FRP jackets. Based on their experimental results, they found that the confinement ratio of sections decreases as the aspect ratio increases. Additionally, they proposed a new stress-strain model for rectangular RC columns fully confined with FRP. Shayanfar and Barros [9] conducted research on a design-oriented model for circular and non-circular FRP RC columns. They proposed a new design-oriented stress-strain model that is applicable to both circular and rectangular RC columns. Lam and Teng proposed a simple design-oriented stress-strain model for RC columns with rectangular cross-sections wrapped externally with FRP. This model predicts the compressive behavior of columns under pure axial load.

The objective of this study is to evaluate the effect of edge sharpness on the axial behavior of rectangular sections externally confined by CFRP sheets using analytical methods. While most research has focused on circular columns, and many experimental studies have been conducted on rectangular columns, limited attention has been given to the analytical assessment of corner radius effects. This gap in the existing literature underscores the need for a comprehensive analytical investigation into how edge sharpness influences the load-carrying capacity and ductility of CFRP-confined RC columns. This paper seeks to address this gap by providing a more detailed analysis of the efficiency of edge sharpness in enhancing FRP confinement for rectangular columns.

2. Material Properties

FRP composite RC columns consist of three primary materials: plain cement concrete, reinforcing steel, and FRP jackets, each with distinct mechanical properties. Concrete is a complex material known for its high compressive strength but low tensile strength, making compressive strength a critical parameter for structural engineers. Under pure axial loads, concrete exhibits elastic-plastic behavior, and its elastic modulus varies depending on factors such as compressive strength, aggregate properties, and age.

Hognestad [10] proposed a parabolic model to describe the stress-strain behavior of unconfined concrete under pure axial compression, as presented in Table 1. In this study, the unconfined concrete has a compressive strength of 25 MPa, and its mechanical behavior under pure axial compression is illustrated in Figure 1a. Steel reinforcement, commonly known as rebar, is used to provide sufficient tensile strength in combination with concrete in RC columns. The high tensile strength of steel compensates for the tensile weakness of concrete, enhancing both the strength and ductility of reinforced concrete columns. In this paper, Grade 60 mild steel with specified structural properties is used, and its mechanical behavior under pure tensile stress is depicted in Figure 1c. FRP is a composite material characterized by high tensile strength, lightweight properties, and excellent durability, created by combining carbon fibers with a polymer matrix [1]. It is widely employed in retrofitting RC columns due to its advantageous mechanical properties. When applied to RC columns, FRP enhances confinement, thereby improving the load-bearing capacity and ductility of the columns. In this study, the FRP sheets have an ultimate tensile strain of 1.6% and an elastic modulus of 220 GPa. The tensile mechanical properties of the FRP are shown in Figure 1d. The relationships between stress and strain for concrete, steel bars, and FRP composites are detailed in Table 1 according to various analytical models, illustrating their structural behavior under axial loads.

Table 1. Properties of cross-sections and materials

Concrete				Longitudinal steel			FRP sheets				Cross-sections		
F_{co} (Mpa)	E_c (Mpa)	ε_{co} (%)	cc (mm)	d_b (mm)	f_y (Mpa)	E_s (Mpa)	E_f (Mpa)	ε_{fu} (%)	nxt_f (mm)	ψ_f	bxh (mmxmm)		
25	23500	0.2	25	16	420	$2x10^5$	$2.2x10^5$	1.6	3x0.135	0.95	300x300	300x450	300x600

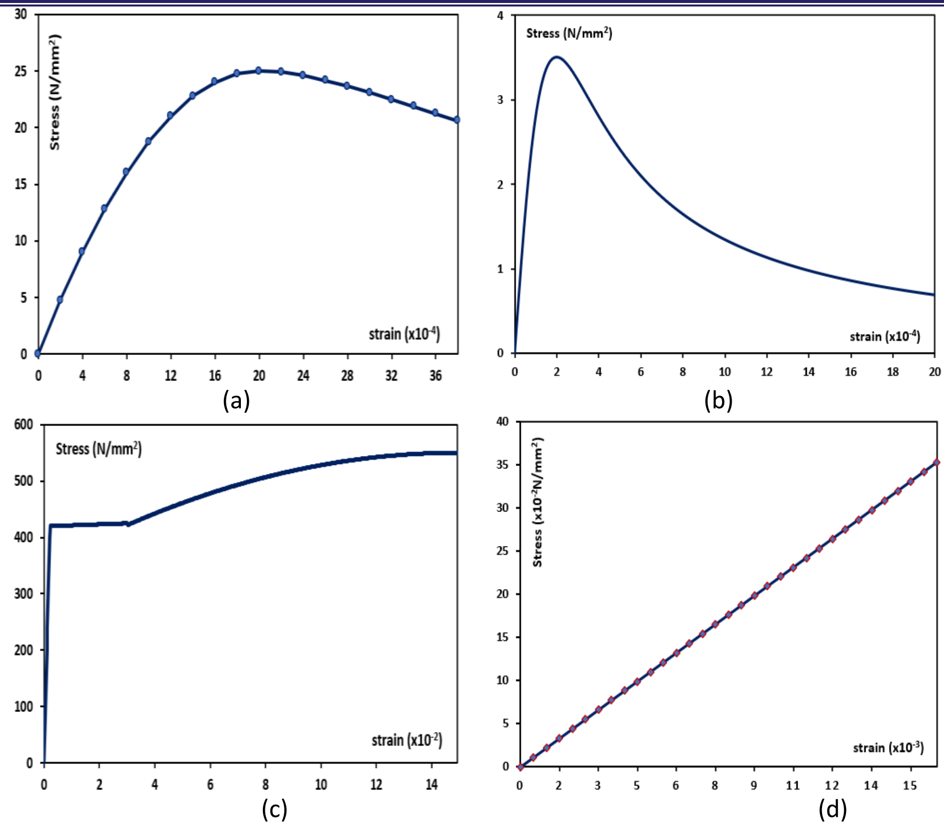


Figure 1. Stress-strain curves: (a) unconfined concrete under compression, (b) unconfined concrete under tension, (c) steel reinforcement under tension, (d) CFRP sheets under tension

3. Methodology

This study investigates the influence of corner radius on the behavior of rectangular cross-section RC columns externally confined with FRP jackets under uniaxial compression using an analytical approach. All column cross-sections are fully wrapped with FRP consisting of three plies, each with a single-layer thickness of 0.135 mm and a tensile elastic modulus of 220 GPa. The mechanical properties of the materials are assumed constants for all cross-sections: the unconfined compressive strength of concrete is 25 MPa, and the yield tensile strength of the longitudinal reinforcement bars is 420 MPa. Based on a review of the literature, several reliable and well-established analytical models for predicting the axial compression behavior of FRP-confined rectangular RC columns are selected to examine key parameters, including the cross-section aspect ratio, corner radius (edge sharpness), material properties, and FRP ply thickness, and their effects on the strength and ductility of the columns.

The relationship between the corner radius ratio and the shape factor, which represents the effective confinement area, was extensively evaluated and illustrated using graphical representations. For more comprehensive results, three rectangular RC columns with dimensions of 300 × 300 mm, 300 × 450 mm, and 300 × 600 mm—corresponding to aspect ratios of 1, 1.5, and 2, respectively— as shown in Figure 2 were analyzed with varying corner radii of 0, 30, 60, 90, 120, and 150 mm. Additionally, stress-strain curves for all cross-sections with the three aspect ratios were plotted and compared across different corner radii using analytical models. The mechanical properties of materials, including the compressive strength, elastic modulus, and strain corresponding to the peak strength of unconfined concrete; the elastic modulus, tensile yield strength, and diameter of longitudinal steel reinforcement; and the elastic modulus, ultimate strain, and single-layer thickness of the FRP jacket, along with the cross-sectional dimensions, are summarized in Table 1.

Table 2. Summary of stress-strain relationships for concrete, steel reinforcement, and FRP sheets

Model	Stress-strain relationships	Model parameters
Concrete in Compression Hognestad Model [10]	Ascending branch: $f_c = f_{co}\left[\frac{2\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right]$ $(0 \le \varepsilon_c \le 0.002)$ Descending branch: $f_c = 2f_{co}\left[\frac{\varepsilon_c/\varepsilon_{co}}{1+(\varepsilon_c/\varepsilon_{co})^2}\right]$ $(0.002 \le \varepsilon_c \le 0.0038)$	$\varepsilon_{co} = 2f_{co}/E_c$ $E_c = 4700\sqrt{f_{co}}\,(Mpa)$
Concrete in Tension: Carreira and Chu 1986 [11]	$\frac{f_t}{f_{to}} = \frac{\beta \frac{\varepsilon_t}{\varepsilon_{to}}}{\beta - 1 + \left(\frac{\varepsilon_t}{\varepsilon_{to}}\right)^\beta}$	$f_{to} = 0.7\sqrt{f_{co}}\,(Mpa)$ $\beta = \left(\frac{f_{co}}{32.4}\right)^3 + 1.55$ $\varepsilon_{to} = \varepsilon_{co}/10$
Steel in Tension [12]	$f_s = E_s\varepsilon_s$ for $\varepsilon_s \le \varepsilon_y$ $f_s = f_y + (\varepsilon_s - \varepsilon_y)\left(\frac{f_{sh} - f_y}{\varepsilon_{sh} - \varepsilon_y}\right)$ for $\varepsilon_y < \varepsilon_s \le \varepsilon_{sh}$ $f_s = f_y + (f_u - f_y)\left[2\left(\frac{\varepsilon_s - \varepsilon_{sh}}{\varepsilon_u - \varepsilon_{sh}}\right) - \left(\frac{\varepsilon_s - \varepsilon_{sh}}{\varepsilon_u - \varepsilon_{sh}}\right)^2\right]$ for $\varepsilon_{sh} < \varepsilon_s \le \varepsilon_u$	$\varepsilon_y = \frac{f_y}{E_s}$ $E_s = 2\times 10^5\,Mpa$
FRP in Tension [1]	$f_f = E_f\varepsilon_f$ $\varepsilon_f \le \varepsilon_{fu}$	-

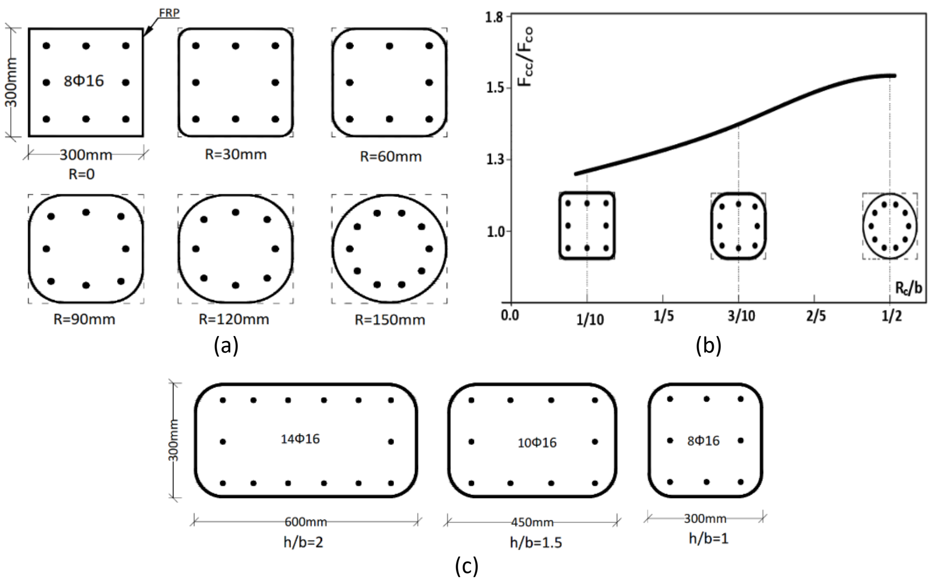


Figure 2. a) Square confined RC columns with various corner radius, b) relationship between normalized strength with corner radius ratios, c) rectangular FRP wraps RC columns with various aspect ratio

3.1. Proposed models for stress-strain prediction

3.1.1 ACI 440.2R-08 confinement model

For rectangular reinforced concrete columns externally confined solely with FRP, a predictive model was proposed by Lam and Teng [13]. This model has been adopted by the ACI Committee [2] for FRP-confined concrete, as illustrated in Figure 3, and can be computed using the following expressions:

$$\sigma_c = \begin{cases} E_c\varepsilon_c - \frac{(E_c - E_2)^2}{4f_{co}}\varepsilon_c^2 \Rightarrow 0 \le \varepsilon_c \le \varepsilon_t \\ f_{co} + E_2\varepsilon_c \Rightarrow \varepsilon_t < \varepsilon_c \le \varepsilon_{ccu} \end{cases} \quad (1)$$

$$\frac{\sigma_{cc}}{\sigma_{co}} = 1 + 3.3\psi_f \times k_a \times \frac{\sigma_l}{\sigma_{co}} \quad (2)$$

$$f_l = \frac{2nE_f t_f \sigma_{fu}}{\sqrt{b^2 + h^2}} \quad (3)$$

Where, σ_c and ε_c represent the compressive stress and strain of concrete, respectively, while E_c and E_2 denote the slopes of the first and second branches of the stress-strain curve, σ_{co} refers to the unconfined compressive strength of concrete in a cylindrical test Ψ_f is an additional reduction factor, set to 0.95. Furthermore, σ_{fu} and E_f represent the ultimate tensile strength and elastic modulus of the FRP, respectively, and b/h describes the aspect ratio of the rectangular cross-section.

The stress-strain relationship proposed by Lam and Teng [13] is illustrated in Figure 3. This curve consists of two different mathematical functions: parabolic and linear. It is applicable to RC columns confined solely with external FRP sheets and does not account for the effects of stirrups or hoops.

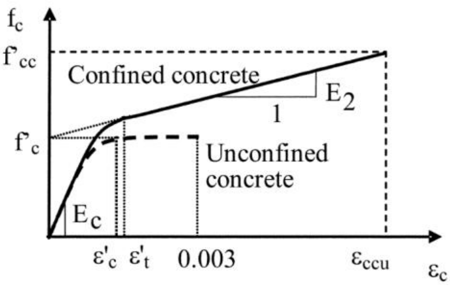


Figure 3. Lam and Teng [13] model for FRP-confined columns

According to the recommendations of the ACI code, the ultimate tensile stress of FRP jackets is calculated using the following expression.

$$\sigma_{fu} = E_f \varepsilon_{fe} = E_f \kappa_\varepsilon \varepsilon_{fu} \quad (4)$$

Here, ε_{fu} represents the rupture strain of FRP wraps, while k_ε denotes the FRP strain efficiency coefficient, with a value for $k_\varepsilon = 0.586$ as recommended by Lam and Teng [13]. Additionally, k_a and k_b are the shape efficiency factors, whose values depend on the effective confinement area and the aspect ratio. For circular cross-sections, k_a equals 1, while for rectangular shapes, it can be determined using the following equation.

$$k_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2 \quad (5)$$

$$k_b = \frac{A_e}{A_c}\left(\frac{h}{b}\right)^{0.5} \quad (6)$$

Where A_e/A_c represents the effective confinement area ratio, which is directly related to the corner radius. The effective confinement area for an FRP-confined rectangular cross-section is shown in Figure 4. This ratio increases with a larger corner radius and is expressed as follows [2]:

$$\frac{A_e}{A_c} = \frac{1 - \dfrac{\left[\left(\dfrac{b}{h}\right)(h-2r_c)^2 + \left(\dfrac{h}{b}\right)(b-2r_c)^2\right]}{3A_g} - \rho_g}{1-\rho_g} \quad (7)$$

The maximum compressive strain in FRP-confined concrete, ε_{ccu}, which represents the ductility of the column, can be determined using the following expression [2].

$$\varepsilon_{ccu} = \varepsilon_{co}\left(1.5 + 12k_b \frac{f_l}{f_{co}}\left(\frac{\varepsilon_{fe}}{\varepsilon_{co}}\right)^{0.45}\right) \le 0.01 \quad (8)$$

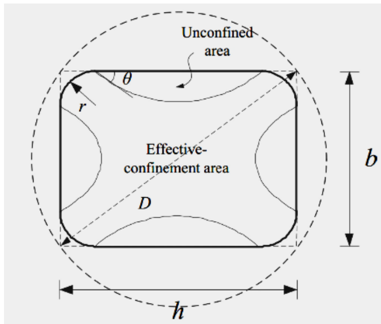


Figure 4. Effective area of confined rectangular column (Lam and Teng [13])

Here, A_e denotes the effective confinement area of the section, A_c represents the total cross-sectional area of the concrete, and A_g is the gross cross-sectional area of the column with rounded corners which is obtained as follows. Additionally, R_c is the corner radius, and ρ_g refers to the longitudinal steel percentage of the column.

$$A_g = bh - (4-\pi)R_c^2 \quad (9)$$

The maximum theoretical axial load capacity (P_n) of an axially loaded RC column fully confined with FRP wraps along its entire length can be determined using the guidelines provided in ACI-440.2R-08 [2], as follows:

$$P_n = \alpha\left[0.85 f_{cc}(A_g - A_{st}) + A_{st} f_y\right] \quad (10)$$

Where α is the accidental eccentricity reduction factor, with α=0.8 for tied columns and α=0.85 for spiral columns; A_{st} represents the total area of longitudinal steel, and f_y denotes the yield tensile strength of the reinforcing steel.

3.1.2 Wei and Wu model

The two-branch unified simple confinement model proposed by Wei and Wu [8] consists of a parabolic curve in the first segment and a straight line in the second segment. This model is applicable to confined FRP RC columns with circular, rectangular, and square cross-sections. In the first segment of the curve, the initial slope corresponds to the elastic modulus of unconfined concrete Ec, while the slope at the transition point remains consistent across both segments. The model can be expressed in the following general form:

$$f_c = \begin{cases} E_c\varepsilon_c + \dfrac{f_o - E_c\varepsilon_o}{\varepsilon_o^2}\varepsilon_c^2 \rightarrow 0 \le \varepsilon_c \le \varepsilon_o \\ f_o + E_2(\varepsilon_c - \varepsilon_o) \rightarrow \varepsilon_o \le \varepsilon_c \le \varepsilon_{cu} \end{cases} \quad (11)$$

$$E_2 = \frac{f_{cu} - f_o}{\varepsilon_{cu} - \varepsilon_o} \quad (12)$$

The transitional stress f_o and strain ε_o values can be determined using the following equations:

$$f_o = f_{co} + 0.43\left(\frac{2r}{b}\right)^{0.68}\left(\frac{h}{b}\right)^{-1} f_l \quad (13)$$

$$\varepsilon_o = \frac{(f_o + f_{cu} + E_c\varepsilon_{cu}) - \sqrt{(f_o + f_{cu} + E_c\varepsilon_{cu})^2 - 8f_oE_c\varepsilon_{cu}}}{2E_c} \quad (14)$$

The lateral confining pressure F_L is determined using the following expression:

$$f_l = \frac{2f_{frp}t}{b} = \frac{2E_f\varepsilon_{fu}t}{b} \quad (15)$$

The maximum confined compressive stress and strain of FRP-wrapped RC columns are calculated using the following equations:

$$\frac{f_{cu}}{f_{co}} = 0.5 + 2.7\left(\frac{2r}{b}\right)^{0.4}\left(\frac{f_l}{f_{co}}\right)^{0.73}\left(\frac{h}{b}\right)^{-1} \quad (16)$$

$$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1.7 + 12\left(\frac{f_l}{f_{co}}\right)^{0.75}\left(\frac{f_{30}}{f_{co}}\right)^{0.62}\left(\frac{0.72r}{b} + 0.64\right)^{-1}\left(\frac{h}{b}\right)^{-0.3}$$
(17)

$$\varepsilon_{co} = 0.000937\sqrt[4]{f_{co}}\,(Mpa) \quad (18)$$

Where f_{cu} and ε_{cu} represent the ultimate confined compressive strength of concrete and its corresponding strain, respectively; f_l denotes the lateral confining pressure; f_{30} refers to the peak compressive strength of concrete with a value of 30 MPa; b and h are the smaller and larger dimensions of the cross-section, respectively; f_{co} and ε_{co} indicate the peak strength and strain of unconfined concrete, respectively; and E_c and E_2 are the slopes of the first and second branches of the stress-strain curve, respectively.

3.1.3 Wu et al. model

They propose a two-part stress-strain relationship for RC columns confined with FRP sheets that is suitable for rectangular cross section. The first branch follows the parabolic law, and its slope is same as well as elastic modulus of unconfined concrete and the second portion of stress-strain curve is linear, and model is given by the following expressions [14]:

$$f_l = \frac{1}{2}\rho_f f_f \quad (19)$$

$$\rho_f = \frac{2(b+h)t_f}{bh} \quad (20)$$

$$f_t = f_{co}\left(1 + 0.0008\alpha k_1\lambda_1\right) \quad (21)$$

$$\varepsilon_t = \varepsilon_{co}\left(1 + 0.0034\alpha k_2\lambda_1\right) \quad (22)$$

where, F_t and ε_t represent the transitional stress and the corresponding strain, respectively; F_{cu} and ε_{cu} denote the ultimate confined stress and strain of the concrete, respectively; and ρ_f is the volumetric ratio of FRP sheets to the concrete cross-section.

4. Analytical Study

4.1. Effect of corner Radius

Numerous experimental and analytical studies have investigated the structural compression behavior of rectangular RC columns retrofitted externally with FRP jackets, focusing on the factors influencing confinement effectiveness [5–7, 15]. One crucial parameter is the corner radius, which directly affects the axial compressive behavior of confined columns. This parameter plays a significant role in the distribution and concentration of lateral confining stresses at the corners, the shape factor, and the peak confined compressive strength and strain of the concrete.

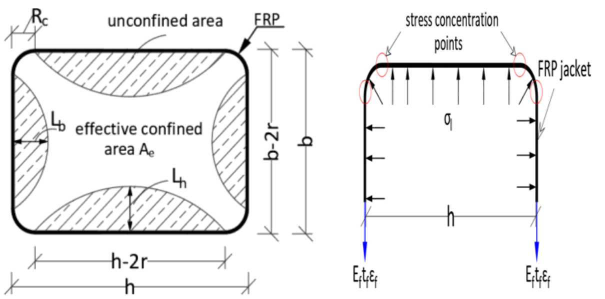
Table 3. Shape factor and peak confined strength

Model	Shape factor	Ultimate stress
Al-Salloum and Youssef [7]	$k_a = 1 - \frac{2}{3}\left[\frac{\left(1-\frac{2r}{b}\right)^2}{1-(4-\pi)\left(\frac{r}{b}\right)^2}\right]$	$\frac{f_{cc}}{f_{co}} = 1 + 3.14 k_a \frac{b}{D}\left(\frac{f_l}{f_{co}}\right)$
Lam and Teng [13]	$k_a = \frac{1 - \frac{\left[\left(\frac{b}{h}\right)(h-2r_c)^2 + \left(\frac{h}{b}\right)(b-2r_c)^2\right]}{3A_g} - \rho_g}{1-\rho_g}\left(\frac{b}{h}\right)^2$	$\frac{f_{cc}}{f_{co}} = 1 + 3.3 k_a \left(\frac{f_l}{f_{co}}\right)$
Youssef et al. [18]	$k_a = 1 - \frac{(b-2r_c)^2 + (h-2r_c)^2}{3bh(1-\rho_g)}$	$\frac{f_{cc}}{f_{co}} = 0.5 + 1.225\left(\frac{k_a f_l}{f_{co}}\right)^{3/5}$
Saleem and Pimanmas [19]	$k_a = 1 - A_1 - A_2$ $A_1 = \frac{(b-2r_c)^2 + (h-2r_c)^2}{3bh}$ $A_2 = \frac{4r_c^2 - \pi r_c^2}{bh}$	$\frac{f_{cc}}{f_{co}} = 0.56 + 3.3\left(\frac{f_l}{f_{co}}\right)$
CNR DT 2004 [20]	$k_a = 1 - \frac{(b-2r_c)^2 + (h-2r_c)^2}{3bh}$	$\frac{f_{cc}}{f_{co}} = 1 + 2.6\left(\frac{f_l}{f_{co}}\right)^{2/3}$
FIB 2019 [21]	$k_a = 1 - \frac{(b-2r_c)^2 + (h-2r_c)^2}{3bh}$	$\frac{f_{cc}}{f_{co}} = 1 + 3.3\frac{f_l}{f_{co}}$

A confined rectangular RC column cross-section with fully wrapped FRP is presented in Figure 5a. This figure illustrates the confinement effectiveness of FRP-wrapped rectangular RC columns, highlighting the influence of the rounded corner radius. The external FRP sheets are depicted by the thin black outline around the cross-section.

The central region, shown in white, is the most effectively confined area, experiencing the full benefits of FRP jacket confinement. This region undergoes uniform stress variation due to lateral confining pressures. In contrast, the hatched areas near the rounded corners represent unconfined zones, where confinement effectiveness is reduced because of the rectangular geometry, especially when the corner radius is small or sharp. A larger corner radius enhances confinement efficiency by increasing the effective confinement area, distributing lateral stresses more evenly, and reducing stress concentrations along the sides [16].

The confinement efficiency of rectangular columns wrapped with FRP depends significantly on the corner radius and the aspect ratio. Circular cross-sections, which can be viewed as a special case of rectangular sections with large corner radii, offer uniform confinement since the entire concrete area benefits from the FRP wraps. In comparison, rectangular sections demonstrate lower confinement effectiveness, particularly at corners with small radii. Increasing the corner radius substantially improves the confinement of rectangular cross-sections [17].



(a) (b)

Figure 5. Rectangular cross-sections: a) Area of confined and unconfined concrete, b) distribution of lateral pressures.

The distribution of lateral confining pressure σ_l exerted by FRP sheets on a rectangular FRP-wrapped RC column, along with the locations of stress concentration points, is illustrated in Figure 5b. The FRP jackets provide lateral confinement to the concrete, enhancing its peak compressive strength and ductility. Stress concentration points, indicated by red circles, experience higher stress levels due to the sharp curvature of the FRP, which can lead to premature failure of the FRP wraps. Lateral confining pressure, represented by black arrows pointing inward, is most significant near the rounded corners. This pressure is generated by hoop stresses within the FRP sheets, which resist the lateral expansion of the concrete under axial compressive loading [16].

The shape factor Ka is defined as the ratio of the effective confined area Ae to the total concrete area Ac for rectangular FRP-wrapped RC columns. It depends on the cross-sectional dimensions, aspect ratio, rounded corner radius, and the percentage of longitudinal steel reinforcement [2, 9, 15]. The expressions used to calculate the shape factor and peak confined strengh, as proposed by various analytical models, are presented in Table 3.

4.2. Impact of aspect ratio

Various column cross-sections, including rectangular, square, and circular configurations, are illustrated in Figure 6. The confinement efficiency of FRP wraps is evaluated for each section type based on corner radius and aspect ratio. Rectangular cross-sections, the most used in RC structural columns, typically have an aspect ratio greater than one. Their confinement efficiency improves as the aspect ratio decreases and the corner radius increases. Square cross-sections are a specific case of rectangular sections, characterized by an aspect ratio of one and a corner radius ratio $2Rc/b<1$. The efficiency of square sections is primarily influenced by the degree of edge sharpness. Circular cross-sections, another special case of rectangular sections, have both an aspect ratio and a corner radius ratio of one. These sections are particularly well-suited for FRP wrapping, as stress is uniformly distributed across the entire cross-section, making all areas effective in resisting confinement forces [22].

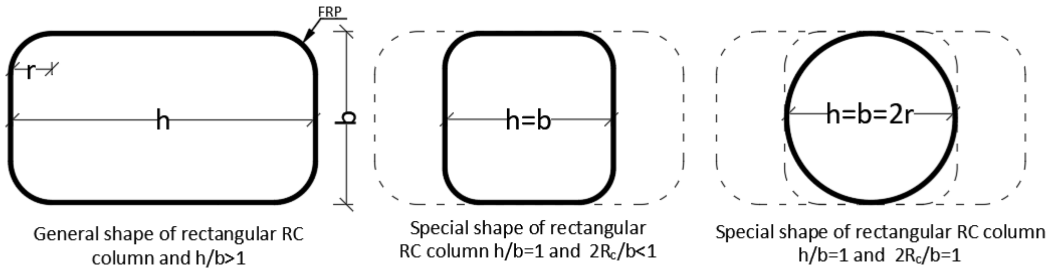


Figure 6. Rectangular cross sections and its special shapes

4.3. Results of parametric study

The relationship between maximum confined compressive strength and the ductility of concrete is illustrated in Figures 7a and 7b for three confined rectangular cross-sections with varying rounded corner radii. According to the figures, the confined peak strength of concrete exhibits significant variation with different aspect ratios.

The column with dimensions 300 × 300 mm and an aspect ratio of 1 demonstrates a higher maximum stress compared to the other two columns. Conversely, the section with dimensions 300 × 600 mm and an aspect ratio of 2 shows lower confined stress at the same corner radius. As shown in Figure 7b, the ultimate confined strain of concrete remains relatively unaffected by changes in aspect ratio. Consequently, the aspect ratio significantly impacts the axial strength of confined FRP-wrapped RC columns, thereby influencing the effectiveness of the corner radius. Furthermore, as the cross-sectional aspect ratio increases, the influence of the corner radius diminishes [23].

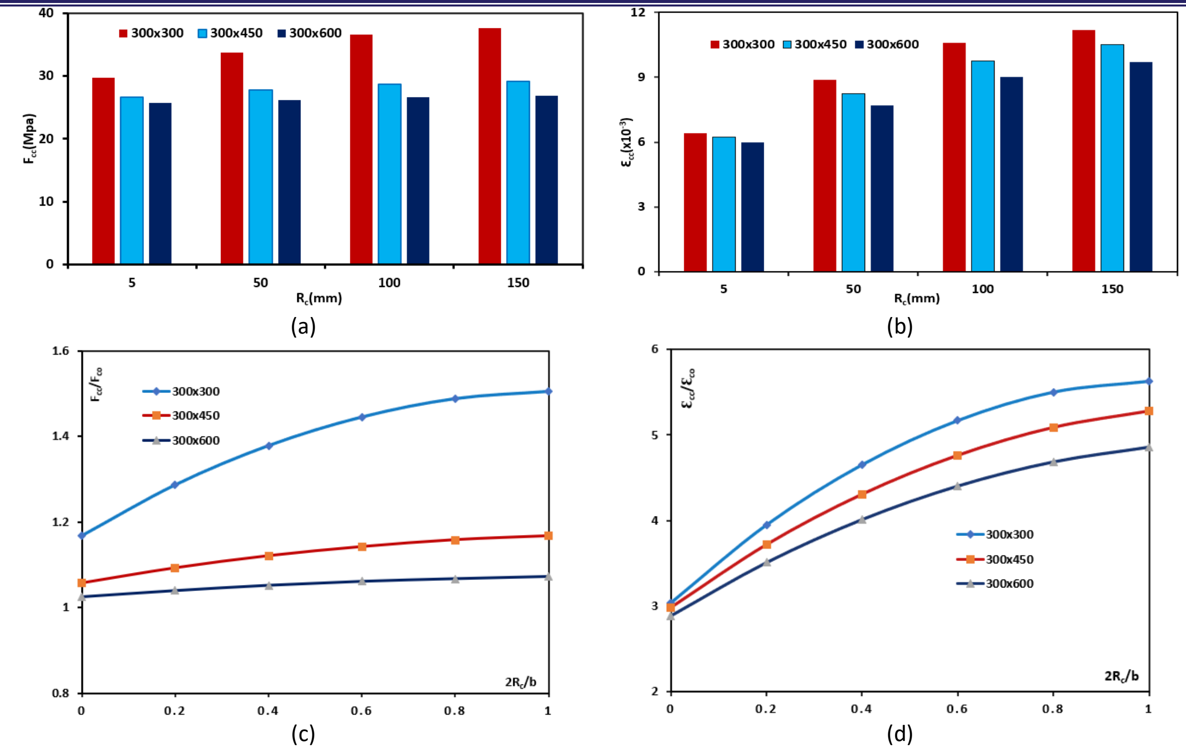


Figure 7. Relationship between strength and ductility with corner radius for various aspect ratio, (a) normalized peak strength with corner radius, (b) maximum confined strain with edge corner, (c) normalized strength with corner radius ratio, (d) normalized strain with corner radius ratio

The normalized peak stress and strain, defined as the ratios of peak stress and strain to the unconfined stress and strain of concrete (F_{cc}/F_{co} and $\mathcal{E}_{cc}/\mathcal{E}_{co}$), are shown in Figures 7c and 7d, respectively, as functions of the corner radius ratio for various aspect ratios. The figures indicate that the corner radius significantly influences square cross-sections, improving confinement efficiency; however, its effect diminishes as the aspect ratio increases. Additionally, for ultimate confined compressive strain, the aspect ratio does not substantially affect the effectiveness of the corner radius, as depicted in Figure 7d. The analytical results presented in Table 6 and Figure 8 demonstrate the influence of varying corner radii on the peak compressive strength (F_{cc}) and ultimate strain ($\mathcal{E}_{ccu}$) of rectangular RC columns strengthened with FRP jackets.

Table 4. Results of the analytical parameters

Sections mm	R_c/b	F_{cc}(Mpa)						$\mathcal{E}_{ccu}$ (%)					
		ACI440.2R-17 [2]	%in	Wei&Wu Model [8]	%in	Wu et al. Model [14]	%in	ACI440.2R-17 [2]	%in	Wei&Wu Model [8]	%in	Wu et al. Model [14]	%in
300x300	0	29.19	0	28.15	0	31.33	0	0.60	0	1.27	0	2.09	0
	0.1	32.16	10.17	31.95	13.50	33.42	6.67	0.78	30	1.34	5.51	2.03	-2.87
	0.2	34.45	18.02	36.45	29.45	35.51	13.34	0.93	55	1.43	12.60	1.95	-6.69
	0.3	36.13	23.77	39.66	40.88	37.60	20.01	1.0	66.6	1.53	20.47	1.88	-10.05
	0.4	37.22	27.51	42.93	52.50	39.68	26.65	1.10	83.3	1.63	28.34	1.81	-13.39
	0.5	37.63	28.91	45.82	62.77	41.77	33.32	1.2	100	1.73	36.22	1.74	-16.74
300x450	0	29.21	0	26.46	0	28.53	0	0.61	0	1.17	0	1.86	0
	0.1	32.19	10.20	28.22	6.65	29.80	4.45	0.79	29.51	1.22	4.27	1.82	-2.15
	0.2	34.50	18.11	30.30	14.51	31.07	8.90	0.93	52.46	1.31	11.96	1.77	-4.84
	0.3	36.19	23.89	32.10	21.32	32.33	13.32	1.04	70.49	1.40	19.66	1.73	-6.99
	0.4	37.28	27.63	33.73	27.47	33.60	17.77	1.10	80.33	1.49	27.35	1.69	-9.14
	0.5	37.71	29.10	35.25	33.22	34.87	22.22	1.13	85.25	1.57	34.19	1.65	-11.29
300x600	0	25.66	0	25.51	0	27.04	0	0.58	0	1.08	0	1.73	0
	0.1	26.02	1.40	26.86	5.29	27.94	3.33	0.70	20.69	1.15	6.48	1.70	-1.73
	0.2	26.31	2.53	28.07	10.04	28.84	6.66	0.80	37.93	1.23	13.89	1.67	-3.47
	0.3	26.54	3.43	29.11	14.11	29.74	9.98	0.88	51.72	1.31	21.30	1.64	-5.20
	0.4	26.70	4.05	30.06	17.84	30.65	13.35	0.94	62.07	1.39	28.70	1.61	-6.94
	0.5	26.80	4.44	30.93	21.25	31.55	16.68	0.97	67.24	1.47	36.11	1.59	-8.09

The analysis examines three confinement models: ACI 440.2R-17 [2], Wei and Wu [8,14], and Wu et al. [14]. As the corner radius ratio (Rc/b) increases from 0 to 0.5, the models show notable variations in performance. Larger corner radii reduce stress concentrations at corners, enhancing confinement efficiency, which leads to improvements in both strength and ductility. Among the models, ACI 440.2R-17 [2] provides conservative estimates, particularly for columns with higher aspect ratios, while the Wei and Wu model predicts greater gains in Fcc and $\mathcal{E}ccu$, reflecting improved confinement behavior. The Wu et al. model [14], although accounting for geometric factors, tends to overestimate peak strength, especially in smaller sections. The ultimate strain proves more responsive to changes in corner radius, underscoring the role of FRP in enhancing ductility. For design purposes, the Wei and Wu model strikes a balance between accuracy and safety [24].

Furthermore, a comparative analysis of peak confined strength and ductility for columns with aspect ratios of 300 × 300 mm, 300 × 450 mm, and 300 × 600 mm reveals that ACI 440.2R-17 [2] often underestimates confinement effects for smaller aspect ratios but overestimates them for larger ones. In contrast, the Wei and Wu [8] model offers more balanced and realistic predictions, particularly in capturing the influence of corner geometry on peak compressive strength.

The effect of the corner radius ratio on the shape factor, or the effective confinement area ratio, is illustrated in Figures 9a and 9c, based on various confinement models and corner radii. According to Figure 9a, rounded corners improve the effective confinement area of rectangular cross-sections, particularly for sections with smaller aspect ratios. For evaluating the shape factor, five analytical models were utilized, including the ACI 440.2R-17 [2] proposed model, Lam and Teng's [13] model, Al-Salloum and Youssef's model [7], the FIB 2019 [21] proposed model, and the model by Youssef et al. [18] and Pimanmas and Saleem [19]. As shown in Figure 9c, four of these models closely agree, while the Pimanmas and Saleem model diverges significantly for larger corner radius ratios. The relationship between the confinement area and cross-sectional aspect ratios is presented in Figure 9b for three corner radius ratios. It is evident that larger corner radius ratios and smaller aspect ratios significantly enhance the effective confinement area. Additionally, the impact of edge sharpness on the theoretical axial load capacity of RC columns is investigated and shown in Figure 9d. The axial compression load capacity of FRP-wrapped rectangular RC columns is directly proportional to the corner radius [23,24].

4.3.1. Stress-strain curves

The stress-strain curves of FRP-confined rectangular reinforced concrete (RC) columns with varying cross-sectional aspect ratios (e.g., 1, 1.5, and 2) and corner radii (e.g., R_c=30 mm, 90 mm, and 150 mm) are compared with those of unconfined concrete, as illustrated in Figures 10a, 10b, and 10c. Unconfined concrete demonstrates brittle compression behavior, characterized by a sharp peak stress followed by a rapid decline and limited axial strain. In contrast, FRP-wrapped RC columns exhibit significantly enhanced compression performance, including increased maximum strength and greater ductility. The confinement efficiency in rectangular cross-sections improves with larger corner radii, which critically influence the axial stress-strain response. Analytical curves show that the R_c=30 mm configuration yields lower peak axial stress and reduced ductility compared to larger corner radii. The R_c=90 mm and R_c=150 mm configurations substantially enhance both strength and ductility, with the R_c=150 mm configuration achieving more uniform stress distribution and reduced stress concentrations at the corners. This leads to higher peak confined compressive strength and improved ductility. These findings emphasize the importance of incorporating rounded corners to enhance confinement efficiency and mitigate stress concentrations in FRP-confined rectangular RC columns.

The axial stress-strain behavior of FRP-wrapped RC columns with dimensions of 300 × 300 mm and an aspect ratio of h/b=1, including a corner radius ratio of R_c/b=0.1, is illustrated in Figure 10d using three analytical models: the ACI recommended model [2], the Wei and Wu model [8], and the Wu et al. model [14]. The curve generated by the ACI model exhibits lower initial stiffness compared to the other two models, although the differences in ultimate strength are minimal.

Conversely, the Wu et al. model overestimates ductility relative to the other models. While its overall behavior is similar to that of the Wei and Wu model, the transitional point between elastic and plastic behavior differs. The Wei and Wu model represents an intermediate response between the ACI and Wu et al. models, with results closely aligned to both. The initial slopes of the ACI and Wei and Wu models are identical, corresponding to the elastic modulus of unconfined concrete, E_c. All three models provide comparable predictions for the ultimate confined compressive strength of concrete, confirming their reliability for modeling rectangular cross-sections. Each model comprises two mathematical branches: an initial parabolic segment followed by a linear portion. This study primarily emphasizes the ACI model, with many parameters derived from its formulations.

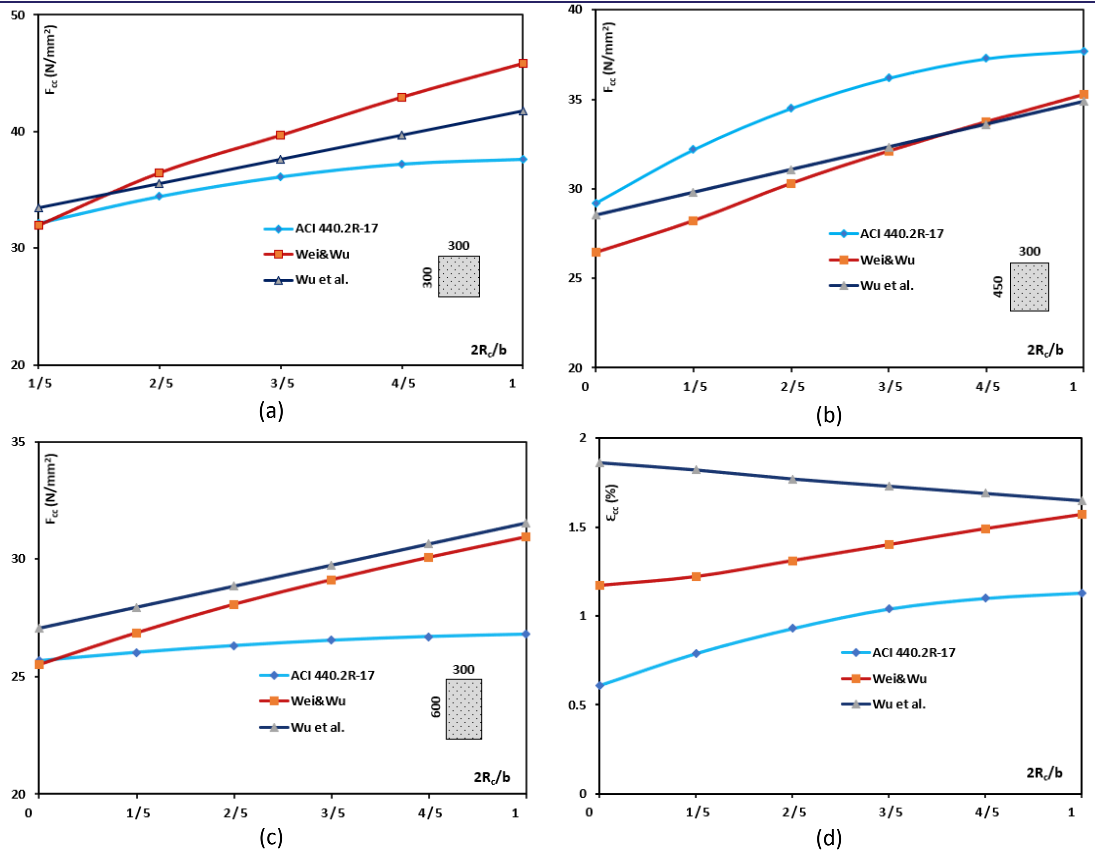


Figure 8. Relationships between peak confined stress and strain for various aspect ratios based on three confinement models.

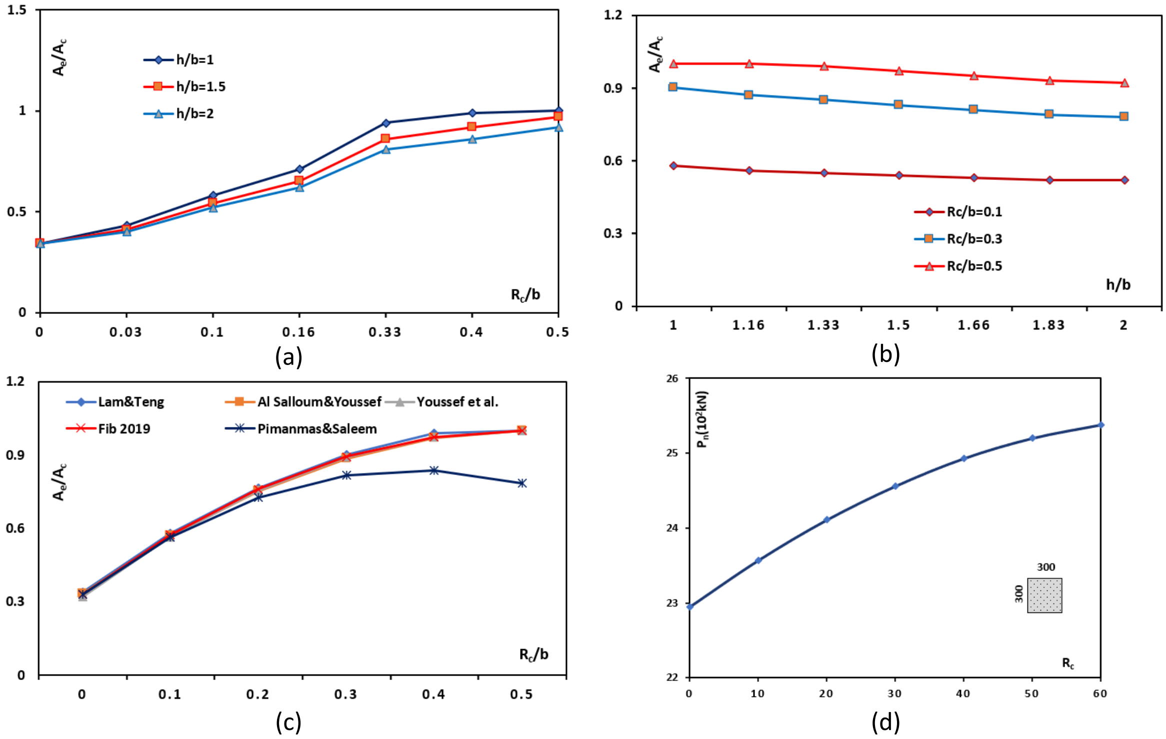


Figure 9. (a) Relationship between confinement area ratio with corner radius ratio, (b) shape factor and aspect ratio, (c) shape factor and corner radius ratio, (d) nominal axial load capacity and corner radius

According to Figure 10, the effectiveness of the corner radius in rectangular FRP-confined RC columns is influenced by the cross-sectional aspect ratio. For smaller aspect ratios (e.g., b/h=1), the impact is pronounced, leading to significant increases in both strength and ductility. As illustrated in Figure 10a, the maximum stress and strain exhibit considerable differences. However, for larger aspect ratios, such as h/b=2, the influence of the corner radius is less pronounced, as shown in Figure 10c. In this case, the stress and strain values for the three corner radii are similar, indicating that the effect of the corner radius diminishes as the aspect ratio increases.

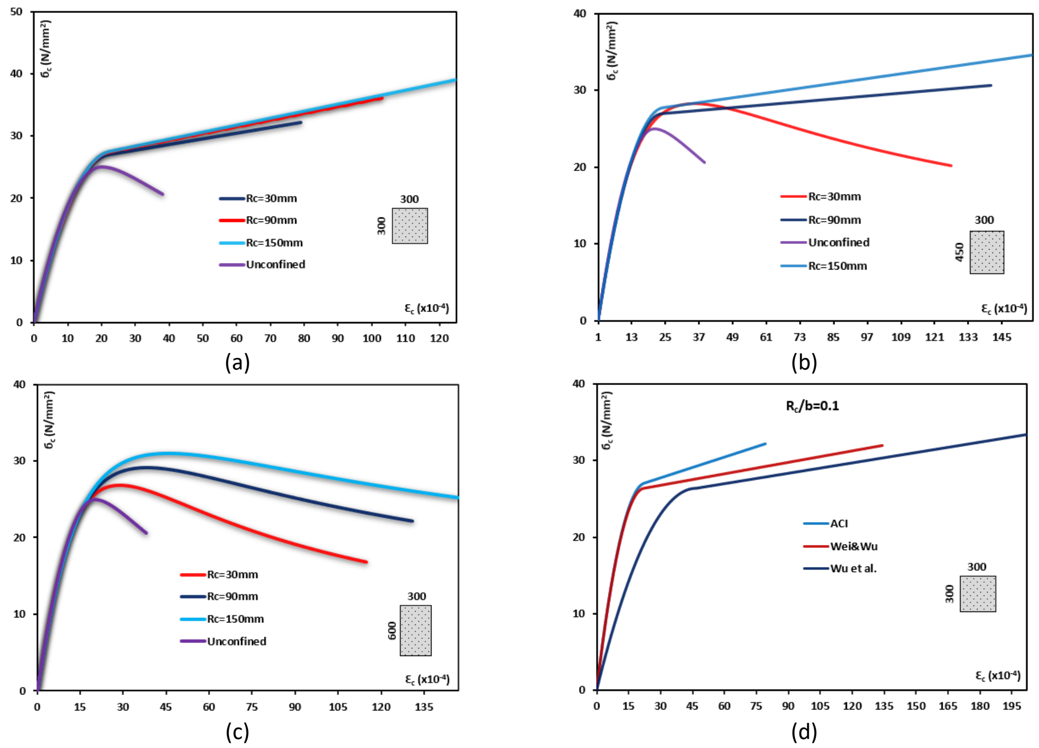


Figure 10. Stress-strain curves based on corner radius, (a) square RC column, (b) rectangular section with aspect ratio of 1.5, (c) rectangular section with aspect ratio of 2, (d) comparison of stress-strain based three models

5. Conclusions

This paper presents a comprehensive analytical investigation into the influence of corner radius on the axial compressive behavior of rectangular reinforced concrete (RC) columns wrapped with fiber-reinforced polymer (FRP) jackets. The findings highlight the significant impact of edge sharpness on confinement efficiency, which directly affects both the strength and ductility of RC columns subjected to pure axial loads. The study evaluates rectangular cross-sectional shapes with aspect ratios of 1.0, 1.5, and 2.0, along with six corner radii (0, 30, 60, 90, 120, and 150 mm). Established analytical models are utilized to examine key parameters, including the shape factor, maximum confined compressive strength, confined strain capacity of concrete, and nominal theoretical axial load capacity. The results indicate that edge sharpness plays a critical role in determining the stress distribution and overall performance of FRP confinement. Larger corner radii improve confinement efficiency by reducing stress concentrations at the edges and expanding the effective confinement area, leading to higher peak compressive strength and enhanced ductility in rectangular sections. Conversely, sharp corners restrict the distribution of lateral confining stresses, thereby diminishing the effectiveness of FRP wraps. The influence of corner radius is most significant in square cross-sections with an aspect ratio of 1.0, where it markedly affects axial strength capacity. In contrast, for rectangular sections with higher aspect ratios, its impact decreases as stress distribution becomes less sensitive to edge geometry. Among the analytical models evaluated, the Wei and Wu [8] model provided a well-balanced prediction of both strength and ductility, demonstrating strong consistency with improved confinement behavior across various corner radius.

The ACI 440.2R-17 [2] model yielded conservative estimates, particularly for columns with smaller corner radii, while the Wu et al. [14] model tended to overestimate strength, especially for columns with lower aspect ratios. These variations highlight the critical need to select an appropriate analytical model tailored to specific geometric configurations and loading conditions when designing FRP-confined RC columns. When the corner radius reaches 150 mm, a square section exhibits confinement behavior similar to that of a circular section, offering enhanced performance due to the uniform distribution of lateral stresses at the corners. This finding underscores the advantages of rounding corners to maximize the effectiveness of FRP wraps in retrofitting and strengthening applications. Additionally, the results show that the shape factor—defined as the ratio of the effective confinement area to the total cross-sectional area—increases significantly with larger corner radii, particularly in square and low-aspect-ratio rectangular sections. In conclusion, this study emphasizes the critical role of corner geometry in the design and retrofitting of rectangular RC columns with FRP confinement.

Declaration of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this article. No financial, professional, or personal relationships influenced the research, analysis, or conclusions presented in this study.

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