

# Retrofitting of Reinforced Concrete Columns Using Fiber Reinforced Polymer Composites: A Review

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**Abstract** - Structural members such as beams and columns may undergo substandard detailing of steel reinforcement, deterioration of concrete and steel under severe environmental attacks such as earthquakes, fire accidents and marine exposure. In such cases replacement of full structure will be expensive due to material and manpower and also creates an impact on culture considering heritage structures such as temples. The other solution for this problem is to retrofit these damaged and deteriorated structural members to meet the exposure conditions. Repair and rehabilitation of Reinforced Concrete (RC) structures can be generally carried out by conventional techniques such as concrete and steel jacketing. Now-a-days some advanced retrofitting methods such as external prestressing and Fiber Reinforced Polymer (FRP) composite wrapping etc. have become popular due to their excellent properties such as corrosion resistance, durability, ease of application and adding less dead weight to the structure without affecting the aesthetic appearance. The aim of this paper is to provide a overview of experimental studies and analytical models available for retrofitting of RC columns using FRP composites. This paper focuses on retrofitting of RC rectangular columns which is most common in heritage structures without modifying the shape of the cross section. The paper also highlights the design guidelines and recommendations available for retrofitting of RC columns with side aspect ratio greater than 2.0 and identifies potential research gaps for further research in the field of retrofitting of RC columns.

**Keywords:** Retrofitting, columns, aspect ratio, FRP composites.

## I. INTRODUCTION

The performance of a structure is defined by its structural stability, life safety and utility. Natural disasters such as hurricanes, tornadoes, tsunamis, earthquakes and accidental impacts will damage and destroy load bearing and framed structures in a short duration. Columns are the primary load carrying members in framed structures, the load carrying capacity and failure modes of these members are critical in assessing the stability of structures. The failure of a RC

column may be due to additional loading, deficiency in shear capacity, improper confinement of core concrete, splicing of longitudinal rebars and corrosion of steel reinforcement. These deficient structures can be re-strengthened by retrofitting. Retrofitting and rehabilitation of RC structures can be done by concrete jacketing, steel jacketing, external prestressing and fiber reinforced polymer (FRP) composite wrapping. Steel jacketing is susceptible to corrosion, increases the dead weight of the columns and application is labor intensive. Concrete jacketing increases the dead weight of structure, attracts higher seismic mass and minimizes the working space. FRP composite wrapping is preferred than concrete and steel jacketing due to its excellent mechanical properties such as high strength to weight ratio, high stiffness to weight ratio, corrosion resistance, durability and ease of application in a short period. The addition of dead weight on structures due to FRP composite wrapping is minimum compared to concrete and steel jacketing.

## Nomenclature

$A_c$	:	Area of core concrete
$A_e$	:	Effective area of confined concrete
$A_g$	:	Gross cross-sectional area of column
$b$	:	Breadth or Width of column
$c$	:	Distance from extreme compression fiber to the neutral axis
$h$	:	Depth of column
$d$	:	Effective depth of cross section
$d_e$	:	Equivalent diameter of noncircular section
$f'_{co}$	:	Compressive strength of unconfined concrete
$f'_{cc}$	:	Compressive strength of confined concrete
$f_{frp}$	:	Tensile strength of FRP composite
$f_l$	:	Lateral confining pressure
$f_b, F_l$	:	The smaller and greater effective lateral confining pressures by Wang and Hsu
$f'_l$	:	Effective lateral confining pressure
$f_y$	:	Yield strength of steel rebar

$t_{frp}$	: Thickness of FRP composite
$k$	: Stiffness coefficient in accordance to Challal et al.
$k_1, k_{s1}, k_{s2}$	: Enhancement factors in accordance to Lam and Teng
$k_1$	: Confinement effectiveness coefficient in accordance to Mimiran and Shahawy
$k_a$	: Shape factor in accordance ACI 440.2R-17
$k_{e2}$	: Coefficient of effect of varying the corner radius by Toutanji et al
$k_{e3}$	: Coefficient of effect of aspect ratio by Toutanji et al
$k_e$	: Shape factor in accordance to Youssef
$k_s$	: Enhancement factors in accordance to Ouyang and Liu
$M_n$	: Nominal moment carrying capacity of column
$n$	: No. of layers of carbon fiber fabric
$P_n$	: Nominal axial load carrying capacity of column
$r_c$	: Radius of corner
$y_t$	: Distance from neutral axis to point of transition strain in compression zone
$\alpha_1, \alpha_2$	: Concrete strength enhancement factors by Wang and Hsu[32]
$\epsilon_{ccu}$	: Compressive strain of FRP confined concrete
$\epsilon_{co'}$	: Compressive strain of unconfined concrete
$\epsilon_s$	: Maximum measured strain in steel rebars
$\epsilon_{sy}$	: Yield strain of steel rebars
$\epsilon_{fe}$	: Effective strain in FRP composite
$\epsilon_{fu}$	: Ultimate strain in FRP composite
$\epsilon_{frp}$	: Maximum measured strain in CFRP composite
$\Psi_f$	: Strength reduction factor in accordance to ACI.2R-17
$\rho_g, \rho_s$	: Steel reinforcement ratio
$\rho_f$	: FRP reinforcement ratio

## II. BEHAVIOR OF CONFINED COLUMNS

The axial stress Vs strain curves of FRP composite confined concrete, steel confined concrete and unconfined concrete are shown in Figure 1. The lateral expansion in unconfined, steel confined and FRP confined concrete is similar up to unconfined strength ( $f_{co}'$ ) and load shedding

started in unconfined concrete column. After yielding, steel jackets induce a constant confining pressure which is not dependent on lateral expansion of concrete. The axial capacity reduces with increase in strain till failure due to ductility of steel plates in steel confined concrete columns. On reaching the unconfined strength in FRP confined columns, FRP composite wrapping will be effective against the lateral expansion developed by cracking of concrete. This induces variable lateral confining pressure which increases the capacity of columns continuously and column fails suddenly on reaching the ultimate strength of FRP fabric.

Carbon fiber reinforced polymer (CFRP) composites are extensively used for retrofitting of RC columns. The effectiveness of the composite wrapping depends upon the cross section of the column and stiffness of the wraps. In RC columns, the lateral confining pressure due to FRP composite wrapping is uniform in circular columns and non-uniform in square and rectangular columns. Due to the non-uniform distribution of lateral confining pressure (Figure 2), the effectiveness of confinement shall be improved by increasing the corner radii ( $r_c$ ) (Toutanji et al.). Many evaluating techniques proposed that result in a minimum modification to the structural geometry, while simultaneously enhancing the structural capacity.

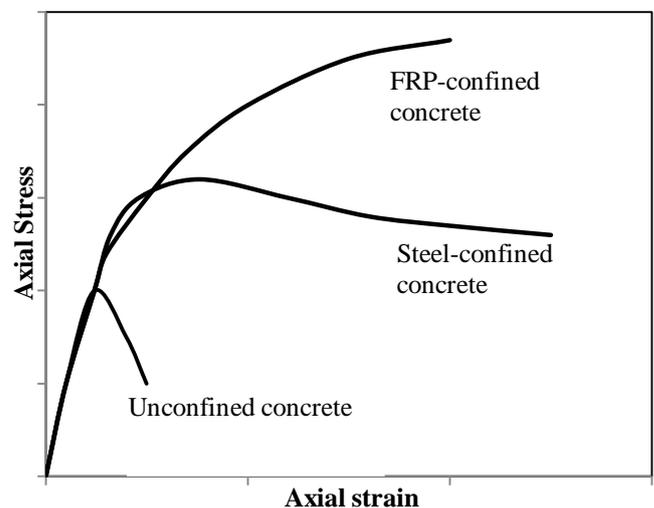


Figure 1: Stress Vs Strain Curves of Unconfined, FRP and Steel Confined Concrete (Source: Spoelstra and Monti[23])

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effectiveness of confinement shall be improved by increasing the corner radii ( $r_c$ ) (Toutanji et al. [30]). Many evaluating techniques proposed that result in a minimum modification to the structural geometry, while simultaneously enhancing the structural capacity.



Figure 2: Effective Confinement Area in Circular, Square and Rectangular Cross Sections (Source: Azadeh and David[3])

The main objective of this paper is to present a representative overview of experimental studies and analytical models of FRP retrofitted RC columns with circular and noncircular cross sections tested under various loading conditions. This paper also identifies potential research areas to address research gaps for future research.

### III. EXPERIMENTAL STUDIES ON RETROFITTING OF RC COLUMNS WITH FRP COMPOSITES

#### 3.1 RC circular columns

A large number of experimental and analytical studies have been carried out to assess the effectiveness of FRP retrofitting on behaviour and failure modes of RC columns with circular cross section.

Berthet et al. [4], Shahawy et al. [22], Samak et al. [20], Mimiran and Shahawy[12] and Yanamoto[34] tested small-scale columns of circular cross-sections strengthened with carbon and E-glass fibre sheets under axial load. It is concluded that FRP strengthening significantly improved the strength and stiffness of RC columns.

Saafi et al. [18] tested new type of concrete columns made of concrete cores encased in PVC tube reinforced with FRP composites to predict the stress strain behaviour.

Micelli et al. [11] tested concrete cylinders confined with FRP composites exposed to environmental cycles and immersed in saline solutions under compressive load. The loss in terms of ductility has been observed in FRP confined columns due to environmental attack.

Kostiha et al. [7] and Vasumathi et al. [31] investigated the compressive behaviour of RC columns with different strengthening techniques using FRP materials such as near surface mounting technique, FRP strips and FRP jackets. It is observed that, the strengthening using FRP jackets exhibits significant strength enhancement compared to other techniques.

#### 3.2 RC square and rectangular columns

RC columns with circular cross-section retrofitted with FRP composites experience a significant increase in strength and ductility compared with columns with rectangular or square cross section. Many researchers suggested that the only possibility to increase the effectiveness of FRP confinement for a rectangular column is modifying the cross-section. The modification can be carried out either by chamfering corners with high corner radii or by attaching separate concrete segments, which are time consuming, adds additional dead weight and occupies more space.

Prota et al. [14] and Tan[27] tested small-scale FRP retrofitted RC rectangular columns with high side aspect ratio of up to 3.65 under axial compression. The effect of change in parameters such as fiber orientation, plaster finish and anchorage were also studied. Tanwongsvat et al.[28] and Teng and Lam[29] tested rectangular columns to predict the effectiveness of FRP composite by modifying the column cross section into an elliptical section. Hollow semi-cylindrical segments were attached to the sides of columns to change the rectangular cross section into an elliptical cross section. Toutanji et al. [30], Roberto and Annalisa[16] and Alireza and Hamed[1] tested prototype wall-like RC columns with aspect ratios varies from 1 to 3.65 retrofitted with FRP composites and studied the effectiveness of FRP composites by changing corner radii, loading conditions, thickness and type of FRP composite.

Tanwongsvat et al. [28] and Toutanji et al. [30] concluded that an increase in aspect ratio reduced the strength enhancement while the others concluded that columns with a high aspect ratio gave significant strength enhancement due to FRP retrofitting. Teng and Lam[29] concluded that the FRP composite strengthening was less effective as the section becomes more elliptical.

Yuvaraj and Mahesh[36] and Reshi and Zakir[15] tested RC columns retrofitted with glass and carbon-fibre composite laminates under axial loading. It is observed that, the premature rupture of FRP fabric at corners can be prevented by providing high corner radii.

Sreelatha and Alagusundaramoorthy[26] tested FRP retrofitted prototype RC rectangular columns with aspect ratio 2.6 without any shape modification of cross section under axial, lateral and combined axial and lateral loading. This is the only test data available for prototype RC rectangular columns under combined axial and lateral loading. From this study, it is observed that the strength and stiffness of RC rectangular columns shall be enhanced by strengthening using CFRP composites without any shape modification. In the extensive literature study, many researchers have reported that the confinement effect of FRP composites does not come into

play until the crushing of concrete. However, it has been experimentally proved by Sreelatha and Alagusundaramoorthy[26] that the confinement effect of CFRP composites can be achieved before the strain in concrete reaches its crushing strain.

A critical review of the available experimental studies indicate that extensive research work has been reported on FRP retrofitted small scale RC circular and rectangular columns with aspect ratio less than 2.0 with modified cross section under axial compression. A very few studies on FRP retrofitted small scale RC rectangular columns with aspect ratio greater than 2.0 under axial loading and lateral loading are reported. Experimental studies are not available in the literature on prototype FRP-retrofitted RC rectangular columns with aspect ratios greater than 2.0 without any shape modification under axial, lateral and combined axial and lateral loading except for Sreelatha and Alagusundaramoorthy[26].

#### IV. ANALYTICAL MODELS

The confinement models are developed by best fitting of experimental data to correlate the stress Vs strain behavior of

confined concrete to the values of various parameters considered in the experimental studies which are believed to be significant.

#### 4.1 RC circular columns

Mander et al. [10] developed a stress–strain model for concrete confined by transverse reinforcement and subjected to uniaxial compressive loading and the confining pressure is assumed to be constant throughout the model. Saadatmanesh et al. [17] extended the Mander’s model to FRP confined columns in which the confining pressure is assumed to be linearly elastic until rupture. Toutanji et al. and Saafi et al. [18] modified the Mander’s model to predict the ultimate strength of PVC-FRP confined concrete. Samaan et al. [19], Xiao and Wu[33] developed models by considering the bi-linear stress strain behaviour of FRP confined concrete. Spolestra and Monti[23] developed a model based on iterative procedure for concrete confined with either steel or FRP. The proposed confinement models proved to be very effective in predicting the increase in strength and ductility. Some important existing empirical models to predict the confined compressive strength of concrete for RC circular columns are presented in Table 1.

**Table 1: Summary of confining models for RC circular columns**

Model	Confined compressive strength of concrete ( $f'_{cc}$ )	Confined compressive strain ( $\epsilon_{cc}$ )
Saadatmanesh et al. [17] (Mander et al. [10])	$f'_{cc} = f'_{co} \left[ -1.254 + 2.254 \sqrt{1 + \frac{7.94 f_l}{f'_{co}}} - 2 \frac{f_l}{f'_{co}} \right]$	$\epsilon_{cc} = \epsilon_{co} \left[ 1 + 5 \left[ \frac{f'_{cc}}{f'_{co}} - 1 \right] \right]$
Toutanji et al.	$f'_{cc} = f'_{co} + 3.5 f_l^{0.85}$	$\epsilon_{cc} = \epsilon_{co} \left[ 1 + (310.57 \epsilon_{fu} + 1.90) \left( \frac{f'_{cc}}{f'_{co}} - 1 \right) \right]$
Saafi et al. [18]	$f'_{cc} = f'_{co} + 2.2 f_l^{0.84}$	$\epsilon_{cc} = \epsilon_{co} \left[ 1 + (537 \epsilon_{fu} + 2.6) \left( \frac{f'_{cc}}{f'_{co}} - 1 \right) \right]$
Samaan et al. [19]	$f'_{cc} = f'_{co} + 6.0 f_l^{0.7}$	$\epsilon_{cc} = (f'_{cc} - f_o) / E_2$ $f_o = 0.872 f'_{co} + 0.371 f_l + 6.258$ $E_2 = 245.61 f'_{co}{}^{0.2} + 1.3456 \frac{E_c t_f}{D}$
Xiao and Wu [33]	$f'_{cc} = f'_{co} + \left( 4.1 - 0.75 \frac{f'_{co}{}^2}{G_j} \right) f_l$	$\epsilon_{cc} = \frac{\epsilon_{fu} - 0.0005}{7 \left( \frac{f'_{cc}}{E_c} \right)^{0.8}}$
Spolestra and Monti [23]	$f'_{cc} = 0.2 f'_{co} + 3 f_l^{0.5}$	$\epsilon_{cc} = \epsilon_{co} \left[ 2 + 1.25 \frac{E_{co}}{f'_{co}} \epsilon_{fu} f_l^{0.5} \right]$

#### 4.2 RC rectangular columns with aspect ratio less than 2.0

In accordance with ACI 440.2R-17[2] and ICBO[6], externally bonded FRP systems are not recommended for RC rectangular columns with aspect ratios greater than 2.0, unless testing demonstrates the confining effect of FRP systems in these columns.

##### 4.2.1 Columns subjected to axial compression

The confining pressure and confining modulus are two significant influence parameters for assessing the behaviour of FRP-confined concrete. For a circular column, the confining pressure is constant around the circumference. As in case of FRP confined rectangular column, the confining pressure is maximum at the corners and minimum at the center of edges. To investigate the confinement effect in rectangular columns, some researchers proposed the concept of equivalent cylinder (Figure 3).

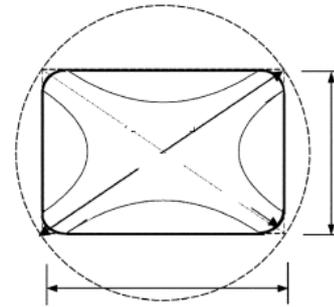


Figure 3: Effective Confining Region for Rectangular Column due to Arching Action (Source: ACI 440.2R-17[2])

Ouyang and Liu[13], Wang and Hsu[32], Toutanji et al. [30], Youssef [35] and Challal et al. [5] developed confinement models for small scale FRP confined RC square columns and rectangular columns with aspect ratio less than 2.0. Lam and Teng[8] developed a model for RC rectangular columns by modifying the cross section into an elliptical section. American Concrete Institute (ACI 440.2R-17) and International Conference of Building Officials (ICBO)[6] proposed equation for enhanced compressive strength for rectangular columns with aspect ratio less than 2.0. The developed models are validated well with the test data. Some existing models to predict the confined compressive strength of concrete in RC rectangular columns with aspect ratio less than 2.0 are presented in Table 2.

Model	Confined compressive strength of concrete ( $f'_{cc}$ )	Confined compressive strain ( $\epsilon_{cc}$ )
ACI 440.2R-17 <sup>[2]</sup>	$f'_{cc} = f'_{co} + \Psi_f 3.3 k_a f_l$ $k_a = \frac{A_e}{A_c} \left(\frac{b}{h}\right)^2$	$\epsilon_{cc} = \epsilon_{co} \left[ 1.50 + 12k_b \frac{f_l}{f'_{cc}} \left(\frac{\epsilon_{fe}}{\epsilon'_{co}}\right)^{0.45} \right] \leq 0.01$
Ouyang and Liu <sup>[13]</sup>	$f'_{cc} = f'_{co} + 3.8k_s f_l$	$\epsilon_{cc} = \epsilon_{co} + 28.1k_s f_l$
Toutanji et al. <sup>[30]</sup>	$f'_{cc} = f'_{co} + k_1 k_{c2} k_{c3} f'_l$ $k_{c2} = \left[\frac{2r}{D}\right]^{0.1}$ $k_{c3} = \left[\frac{d}{b}\right]^{0.13}$	---
Challal et al. <sup>[5]</sup>	$f'_{cc} = f'_{co} + 4.12 \times 10^5 k$ $k = \frac{E_{FRP} A_{FRP}}{E_c A_c}$	$\epsilon_{cc} = \epsilon_{co} + 10^3 [3k - 150k^2] / f'_{co}$

Youssef <sup>[35]</sup>	$f'_{cc} = f'_{co} \left[ 0.5 + 1.225 \left( \frac{f'_l}{f'_{co}} \right)^{3/5} \right]$ $f'_l = k_e \left( \frac{1}{2} \rho_f f_{FRP} \right)$	$\epsilon_{cc} = 0.004325 + 0.2625 \left( \frac{f'_l}{f'_{co}} \right) \left( \frac{f_{FRP}}{E_f} \right)^{1/2}$
Lam and Teng <sup>[8]</sup>	$f'_{cc} = f'_{co} + k_1 k_{s1} f'_l$	$\epsilon_{cc} = \epsilon_{co} \left[ 1.75 + k_2 k_{s2} \frac{f'_l}{f'_{co}} \left( \frac{\epsilon_{tl}}{\epsilon_{co}} \right)^{0.45} \right]$
ICBO <sup>[6]</sup>	$f'_{cc} = f'_{co} (1 + 5 \rho_f \cos^2 \theta)$	---
Mimiran and Shahawy <sup>[12]</sup>	$f'_{cc} = f'_{co} + k_1 f'_l$ $k_1 = 6.0 f'_l^{-0.3}$	---
Wang and Hsu <sup>[32]</sup>	$f'_{cc} = k_c f'_{co}$ $k_c = \alpha_1 \alpha_2$ $\alpha_1 = 1.25 \left( 1.8 \sqrt{1 + 7.94 \frac{F_1}{f'_c}} - 1.6 \frac{F_1}{f'_c} - 1 \right)$ $\alpha_2 = \left[ 1.4 \frac{f_1}{F_1} - 0.6 \left( \frac{f_1}{F_1} \right)^2 - 0.8 \right] \sqrt{\frac{F_1}{f'_{co}}} + 1$	---

#### 4.2.2 Columns subjected to combined axial compression and bending

Seible et al. [21] developed equations to calculate the flexural moment capacity of RC rectangular column with aspect ratio less than 1.5 subjected to combined axial and lateral loading.

An analytical procedure given in ACI 440.2R-17[2] was used to predict the axial and lateral load carrying capacities of columns strengthened with CFRP composites. The portion of unconfined and confined  $P_n - M_n$  diagrams corresponding to compression-controlled failure can be reduced to two bilinear curves passing through three points (Figure 4). Point 'A' (pure compression) at a uniform axial compressive strain of confined concrete ' $\epsilon_{ccu}$ '. Point 'B' with a strain distribution corresponding to zero strain at the steel reinforcement nearest to the tensile face, and a compressive strain  $\epsilon_{ccu}$  on the compression face (Figure 5a) and point 'C' with a strain distribution corresponding to balanced failure with a maximum compressive strain  $\epsilon_{ccu}$  and a yield strain  $\epsilon_{sy}$  at the steel layer nearest to the tensile face (Figure 5b).

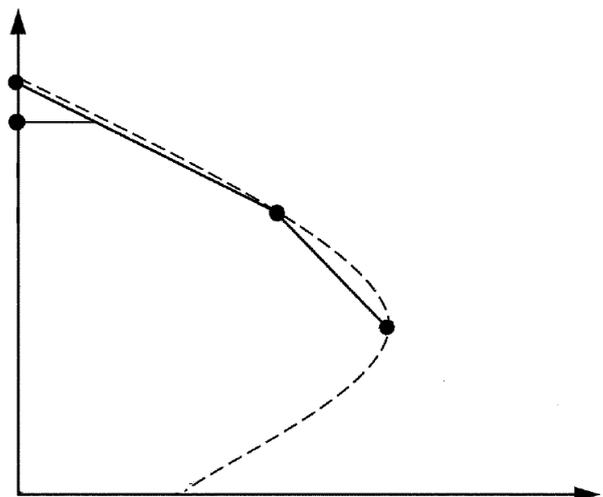


Figure 4: Representative  $P_n - M_n$  Interaction Diagram (Source:ACI 440.2R-17[2])

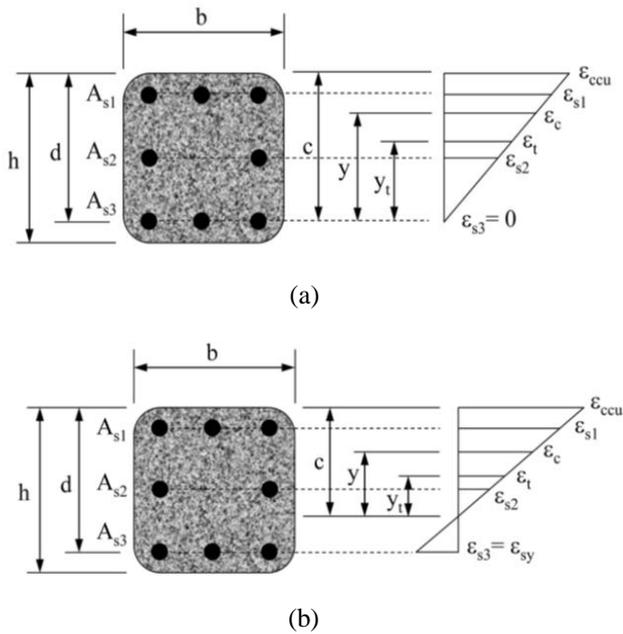


Figure 5: Strain Distributions for Points B and C for Simplified Interaction Diagram (a) Point B and (b) Point C (Source: ACI committee 440.2R-17[2])

The axial load carrying capacity and the moment carrying capacity of RC rectangular columns confined with FRP composites can be calculated using Eq. (1) and Eq. (2) for co-ordinates of points B and C without any safety factors as;

$$P_{n(B,C)} = (A(y_t)^3 + B(y_t)^2 + C(y_t) + D) + \sum A_{si} f_{si} \quad (1)$$

$$M_{n(B,C)} = (E(y_t)^4 + F(y_t)^3 + G(y_t)^2 + H(y_t) + I) + \sum A_{si} f_{si} d_i \quad (2)$$

in which

$$A = \frac{-b(E_c - E_2)^2}{12f'_{co}} \left( \frac{\epsilon_{ccu}}{c} \right)^2 \quad (3)$$

$$B = \frac{b(E_c - E_2)}{2} \left( \frac{\epsilon_{ccu}}{c} \right) \quad (4)$$

$$C = -bf'_{co} \quad (5)$$

$$D = bcf'_{co} + \frac{bcE_2}{2} (\epsilon_{ccu}) \quad (6)$$

$$E = \frac{-b(E_c - E_2)^2}{16f'_{co}} \left( \frac{\epsilon_{ccu}}{c} \right)^2 \quad (7)$$

$$F = b \left( c - \frac{h}{2} \right) \frac{(E_c - E_2)^2}{12f'_{co}} \left( \frac{\epsilon_{ccu}}{c} \right)^2 + \frac{b(E_c - E_2)}{3} \left( \frac{\epsilon_{ccu}}{c} \right) \quad (8)$$

$$G = - \left[ \frac{b}{2} f'_{co} + b \left( c - \frac{h}{2} \right) \frac{(E_c - E_2)}{2} \left( \frac{\epsilon_{ccu}}{c} \right) \right] \quad (9)$$

$$H = bf'_{co} \left( c - \frac{h}{2} \right) \quad (10)$$

$$I = \frac{bc^2}{2} f'_{co} - bf'_{co} \left( c - \frac{h}{2} \right) + \frac{bc^2 E_2}{3} (\epsilon_{ccu}) - \frac{bcE_2}{2} \left( c - \frac{h}{2} \right) \epsilon_{ccu} \quad (11)$$

in which

$$c = \begin{cases} d & \text{for Point B} \\ d \frac{\epsilon_{ccu}}{\epsilon_{sy} + \epsilon_{ccu}} & \text{for Point C} \end{cases} \quad (12)$$

and

$$y_t = c \frac{\epsilon_t}{\epsilon_{ccu}} \quad (13)$$

### 4.3 RC Rectangular Columns with aspect ratio greater than 2.0

#### 4.3.1 Columns Subjected to axial compression

Maalej et al. [9] proposed equations for confined columns with aspect ratio 3.65 with chamfered corners (corner radii of 30 mm). Sreelatha and Alagusundaramoorthy[24] developed semi-empirical equations by modifying ACI 440.2R-17[2] equations for calculating the compressive strength of confined concrete of FRP strengthened RC rectangular columns having aspect ratio greater than 2.0 and without any shape modification by introducing a confinement efficiency coefficient ( $k_c$ ) given as;

$$f'_{cc} = f'_{co} + k_c f_t \quad (14)$$

$$k_c = k_1 k_a \quad (15)$$

In which shape factor ' $k_a$ ' can be calculated as

$$k_a = \frac{A_e}{A_c} \left( \frac{h}{b} \right)^2 \quad (16)$$

The value of ' $k_j$ ' obtained as 1.78 from test results by regression analysis. For columns without any shape modification ' $r_c$ ' is equal to zero. Hence, the equation for  $\frac{A_e}{A_c}$  given by ACI 440.2R-17 reduced as

$$\frac{A_e}{A_c} = \frac{1-3\rho_g}{3(1-\rho_g)} \quad (17)$$

#### 4.3.2 Columns subjected to combined axial compression and bending

Limited experimental and analytical study carried out by Sreelatha and Alagusundaramoorthy[24] FRP confined RC rectangular columns with aspect ratio greater than 2.0 subjected to combined axial and lateral loading, the authors developed interaction diagrams by modifying the ACI 440.2R-17 procedure. As per ACI 440.2R-17,  $P_n - M_n$  interaction diagrams were developed with three points A, B and C (Figure 5). In this study, another point D which represents the pure bending with crushing strain at steel layer nearest to the tensile face is greater than yield strain ( $\epsilon_{sy}$ ) of steel (Figure 6).

The  $P_n - M_n$  co-ordinates at point B and C for FRP strengthened RC rectangular columns having aspect ratio greater than 2.0 and without any shape modification shall be calculated using Eqs. (1) and (18). The Eq. (18) is the modification of Eq. (2) by introducing a constant ' $k$ ' as

$$M_{n(B,C,D)} = [E(y_t)^4 + F(y_t)^3 + G(y_t)^2 + H(y_t) + k I] + \sum A_{si} f_{si} d_i \quad (18)$$

The value of constant ' $k$ ' was obtained as 1.12 and 1.55 for lateral load (Pure bending) and combined axial and lateral loading respectively from the test data by regression analysis.

V. RESEARCH GAPS FOR FUTURE RESEARCH

An overview on the experimental studies conducted to investigate the effectiveness of FRP composites on behaviour of RC columns indicates that the more focus of the research is given for small-scale RC circular and rectangular columns. Very few experimental studies are available on FRP-retrofitted RC rectangular columns with aspect ratios greater than 2.0 under combined axial and lateral loading and that lack necessitates further research work. Tests shall be conducted on these types of columns with and without shape modification under axial, lateral and combined axial and lateral loading to authenticate the test results and to develop analytical models. Future research also needed to determine the sensitiveness of FRP confined systems to environmental effects and saline water attack. There is a necessity for development of design guidelines that take into account the loss in terms of ductility for FRP confined columns.

VI. CONCLUDING REMARKS

This paper presented a detailed overview of experimental studies and analytical models available for retrofitting of RC columns with circular and non-circular cross sections using FRP composites. From the extensive literature study, it is concluded that FRP composites can be effectively used for columns to enhance the stiffness, axial and lateral capacity of columns with and without any shape modification. More emphasis shall be given to the experimental studies on FRP retrofitted prototype RC rectangular columns under various loading conditions.

Further research is necessary to investigate the effectiveness of FRP composites for prototype RC rectangular columns with aspect ratio greater than 2.0 under combined axial and lateral loading. Confining models shall be developed for FRP retrofitted RC columns with aspect ratio greater than 2.0. Guidelines shall be developed for FRP confined columns subjected to environmental attacks. Design recommendations shall be made readily available for more rapid and effective usage of FRP composites to retrofit deficient structures.

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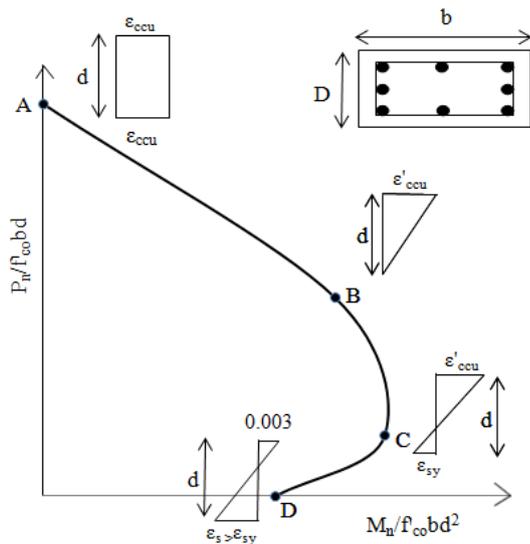


Figure 6: Modified Interaction Diagram (Source: Sreelatha and Alagusundaramoorthy[24])

The developed  $P_n - M_n$  interaction diagrams are validated with the  $P_n - M_n$  interaction diagrams generated from the salient points A, B, C and D obtained through analytical study and observed a good validation. Sreelatha and Alagusundaramoorthy[25] also developed  $P_n - M_n$  interaction diagrams for RC columns having as aspect ratio greater than 2.0 and strengthened without any shape modification using the proposed semi-empirical equations by varying the unconfined compressive strength of concrete ( $f'_{co}$ ) (20, 30 and 40 N/mm<sup>2</sup>), yield strength of steel ( $f_y$ ) (415 and 500 N/mm<sup>2</sup>), percentage of steel reinforcement ( $\rho_s$ ) (0.6, 1.1, 1.8, 2.1 and 2.6) and thickness of FRP composite ( $t_{frp}$ ) (1 layer (0.6 mm) to 3 layers (1.8 mm)). A typical set of interaction diagrams are shown in Figure.

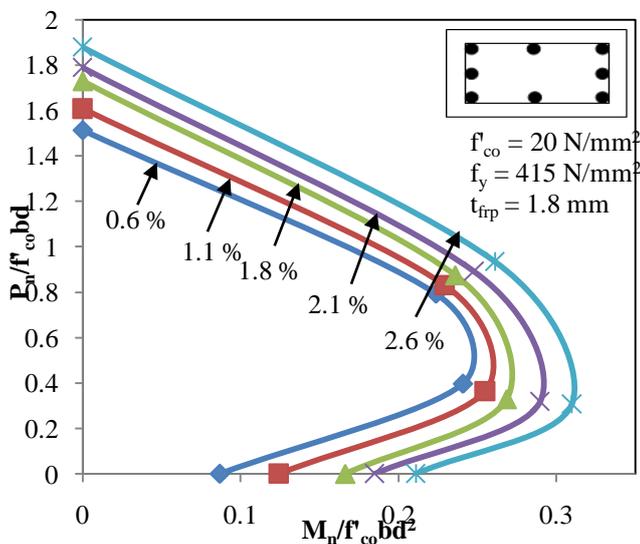


Figure 7:  $P_n - M_n$  Interaction Diagrams for  $f'_{co}$  20 N/mm<sup>2</sup>,  $f_y$  415 N/mm<sup>2</sup> and  $t_{frp}$  1.8 mm (Source: Sreelatha and Alagusundaramoorthy[25])

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