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# FRP Strengthened RC Rectangular Columns Under Combined Axial and Lateral Loading: Analytical Study

Sreelatha Vuggumudi*, P. Alagusundaramoorthy

*Structural Engineering Laboratory, IIT Madras, 600036, India*

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ABSTRACT

Semi-empirical solutions are proposed to predict the axial and lateral capacities of reinforced concrete (RC) rectangular columns having aspect ratio greater than 2.0 strengthened using fiber reinforced polymer (FRP) composites without any shape modification and subjected to axial, lateral and combined axial and lateral loading. 3D finite element models are generated for the analysis of FRP strengthened RC columns. Semi-empirical solutions and finite element models are validated with the test results. Column interaction diagram between axial capacity $P_n$ and bending moment $M_n$ is generated using the proposed semi-empirical solutions and compared with $P_n$ - $M_n$ interaction diagram generated as per ACI 440.2R-08 [1] procedure. From this study, it is concluded that the proposed semi-empirical solutions shall be used for the design of RC rectangular columns having aspect ratio greater than 2.0 strengthened with FRP composites and without any shape modification.

## 1. Introduction

The axial and lateral capacities of RC columns will be significantly reduced due to corrosion of steel reinforcements and these columns are to be repaired and rehabilitated to fulfill the functional requirements. RC columns are to be retrofitted to comply with the capacity as per the revised code provisions and enhance the load carrying capacity as per the demand. FRP composites are widely used to rehabilitate and retrofit RC columns due to their high strength to weight ratio, high stiffness to weight ratio and excellent corrosion resistance. Circular columns can be effectively retrofitted using FRP composites compared to square and rectangular columns due to the uniform distribution of lateral confining pressure in circular sections. The confining pressure is not uniform around square and rectangular sections and maximum at the edges and minimum in between the edges.

Alsayed et al. [2], Prota et al. [10], Tan [15] and Tanwongsval et al. [16] predicted the confinement effect of FRP composites on small scale wall-like RC columns with rectangular and elliptical cross sections having high aspect ratio of 3.65 under axial and sustained axial loading. Reshi and Zakir [12] and Yuvaraj and Mahesh [21] tested RC columns retrofitted with glass and carbon fiber composite laminates under axial loading. Chen and Togay [4], Mohammad et al. [9] and Toutanji et al. [19] tested square and rectangular FRP tubes filled with concrete under axial loading. Mander et al. [7] developed a stress-strain model for concrete confined by stirrups subjected to uniaxial compressive loading and the confining pressure is assumed to be constant throughout the model. This proved to be inadequate for the analysis of FRP confined concrete in which the confining pressure is linearly elastic until rupture. Lam and Teng [5], Samaan et al. [13] and Teng and Lam [17,18] developed a model to predict the bilinear stress-strain response of FRP confined RC rectangular columns by modifying shape of cross section. Maalej et al. [6] proposed an analytical model to predict the load-displacement response of wall-like RC columns with aspect ratio 3.65 strengthened with FRP composites with and without sustained axial loading. Challal et al. [3] and Mimiran and shahawy [8] developed analytical models to predict the axial load carrying capacity of small scale FRP confined RC columns. Seible et al. [14] and Wang and Hsu [20] proposed a design method to evaluate the load carrying capacity of square and rectangular RC columns with aspect ratio less than 2.0 confined with FRP composites under axial and combined axial and lateral loading with shape modification. In literature, extensive research work has been reported on axially loaded RC circular and small scale rectangular columns with aspect ratio less than 2.0 strengthened with FRP composites. Test data, semi-empirical solutions and finite element models are not available for RC rectangular columns having aspect ratio greater than 2.0 strengthened using FRP composites without rounding the corners and subjected to the combined axial and lateral loading.

## 2. Objective and scope

The main objective of the study is to propose semi-empirical

* Corresponding author at: Structural Engineering Laboratory, Civil Engineering Department, IIT Madras, Chennai 600036, Tamilnadu, India.
*E-mail address:* srilathavuggumudi.91@gmail.com (S. Vuggumudi).

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solutions to predict the axial and lateral capacities of RC rectangular columns having aspect ratio greater than 2.0 strengthened using FRP composites without any shape modification and subjected to axial, lateral and combined axial and lateral loading. The scope of work is limited to (i) propose semi-empirical solutions to predict the capacity of RC rectangular columns having aspect ratio greater than 2.0 strengthened using FRP composites and without chamfering the corners, (ii) develop finite element (FE) models using ABAQUS software for FRP strengthened RC rectangular columns having aspect ratio greater than 2.0, (iii) validation of semi-empirical solutions and FE models and with the available test data and (iv) generate $P_n$ - $M_n$ interaction diagram for FRP strengthened RC rectangular columns having aspect ratio greater than 2.0 subjected to combined axial and lateral loading.

## 3. Semi-empirical solutions

The load carrying capacity of FRP strengthened RC rectangular columns depends on the tensile modulus and ultimate strength of FRP composites in warp direction, aspect ratio of column cross section (*depth, h/width, b*) and corner radii ($r_c$) etc. As per literature, the rate of strength enhancement in FRP strengthened RC rectangular columns is reducing for large aspect ratios and small corner radii. The axial and lateral capacities of FRP composite strengthened RC rectangular columns having aspect ratio greater than 2.0 without any shape modification are calculated using the semi-empirical solutions proposed by authors without considering the safety factors and compared with the test data (Table 1). It is observed that the available semi-empirical solutions are under estimating the axial capacities of FRP strengthened RC rectangular columns. The semi-empirical solutions proposed by ACI 440.2R-08 are under estimating the capacity of FRP strengthened RC rectangular columns subjected to lateral and combined axial and lateral loading (Table 1). The procedures given in ACI 440.2R-08 is modified and new semi-empirical solutions are proposed to calculate the load carrying capacity of RC rectangular columns having aspect ratio greater than 2.0 strengthened using FRP composites subjected to axial, lateral and combined axial and lateral loading.

### 3.1. Capacity of columns under axial compression

The semi-empirical solutions given in ACI 440.2R-08 [1] shall be used for columns having aspect ratio less than 2.0. The procedure given in ACI 440.2R-08 is modified to predict the axial load carrying capacity of RC rectangular columns strengthened with FRP composites without rounding the corners having aspect ratio greater than 2.0.

The axial capacity ($P_n$) of RC rectangular column strengthened with FRP composites without any safety factors can be calculated as;

$$P_n = f'_{cc}(A_g - A_{st}) + f_y A_{st} \tag{1}$$

The compressive strength ($f_{cc}$') of FRP-confined concrete is calculated using the Eq. (2) based on the arching action as;

$$f'_{cc} = f'_{co} + k_a f_l \tag{2}$$

The lateral confining pressure '$f_l$' is calculated as;

$$f_l = \frac{2E_f n t_f \varepsilon_{fe}}{D} \tag{3}$$

in which 'D' is the diameter of the equivalent circular cross section of noncircular sections.

The compressive strength of FRP confined RC rectangular columns having aspect ratio greater than 2.0 shall be calculated by introducing a confinement efficiency coefficient in Eq. (2) as

$$f'_{cc} = f'_{co} + k_c f_l \tag{4}$$

in which

$$k_c = k_1\, k_a \tag{5}$$

The value of "$k_1$" shall be obtained from the test data by trial and error method.

The shape factor '$k_a$' depends upon the cross sectional area of effectively confined concrete $A_e$, side aspect ratio "$h/b$" and corner radii "$r_c$" and can be calculated as

$$k_a = \frac{A_e}{A_c}\left(\frac{h}{b}\right)^2 \tag{6}$$

As per ACI 440.2R-08,

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

in which '$\rho_g$' is the ratio of longitudinal steel reinforcement.

The corner radii "$r_c$" is equal to zero for columns without shape modification and Eq. (7) is modified as;

$$\frac{A_e}{A_c} = \frac{1 - 3\rho_g}{3(1 - \rho_g)} \tag{8}$$

Substituting Eqs. (4) and (5) in Eq. (1), the axial capacity ($P_n$) of RC rectangular columns having aspect ratio greater than 2.0 strengthened with FRP composites can be calculated as;

$$P_n = [f'_{co} + k_1 k_a f_l](A_g - A_{st}) + f_y A_{st} \tag{9}$$

The value of "$k_1$" obtained from test results is 1.78.

### 3.2. Capacity of columns under combined axial compression and lateral loading

As per ACI 440.2R-08, $P_n$ - $M_n$ diagrams are generated using the model for the stress-strain behaviour for FRP-confined concrete by satisfying strain compatibility and force equilibrium conditions. The portion of the unconfined and confined $P_n$ - $M_n$ diagrams corresponding to compression controlled failure is reduced to two bilinear curves passing through three points A, B and C.

The $P_n$ - $M_n$ co-ordinates at point B and C shall be calculated as;

$$P_{n(B,C)} = (A(y_t)^3 + B(y_t)^2 + C(y_t) + D) + \sum A_{si} f_{si} \tag{10}$$

**Table 1**
Comparison of available semi-empirical solutions with test data.

| Specimen | Theoretical capacity (kN) | | | | Experimental capacity ($P_{uE}$) (kN) | $P_{uACI}/P_{uE}$ | $P_{uM}/P_{uE}$ | $P_{uLT}/P_{uE}$ | $P_{uC}/P_{uE}$ |
|---|---|---|---|---|---|---|---|---|---|
| | ACI 440.2R-08 ($P_{uACI}$) | Mimiran and shahawy ($P_{uM}$) | Lam and Teng ($P_{uLT}$) | Challal et al. ($P_{uC}$) | | | | | |
| CCA1 | 3256 | 3256 | 3256 | 3256 | 3334 | 0.976 | 0.976 | 0.976 | 0.976 |
| RCA2 | 3958 | 3982 | 4081 | 5389 | 4609 | 0.858 | 0.864 | 0.885 | 1.169 |
| CCL3 | 34 | * | * | * | 33 | 1.03 | * | * | * |
| RCL4 | 40 | * | * | * | 41 | 0.975 | * | * | * |
| CCC5 | 58 | * | * | * | 69 | 0.840 | * | * | * |
| RCC6 | 70 | * | * | * | 89 | 0.786 | * | * | * |