

AXIAL COMPRESSIVE STRENGTH OF REINFORCED CONCRETE COLUMN STRENGTHENING WITH CFRP SUBJECTED TO CONCENTRIC LOADING

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ABSTRACT: This study was an experimental program on the behavior of reinforced concrete short columns confined with CFRP, which is subjected to concentric loading, and developed an equation to predict the axial compressive strength of the column. Four specimens with a size of 75 mm × 75 mm × 750 mm were made and tested. One specimen was the column without CFRP as a reference specimen, while the others were confined with one, two, and three layers of CFRP, respectively. Cylinder specimens were also made with a size of 300 mm × 150 mm to get the compressive strength. The Cylinder specimens were also made in 4 variations: first, without CFRP; second, wrapped with one layer; third, wrapped with two layers; and fourth, wrapped with three layers of CFRP. The results of column testing were compared with several models that have been proposed by previous researchers. The experimental results show that the compressive strength of a column without CFRP, with one CFRP layer, with two layers of CFRP, and with three layers of CFRP were 121372.12 N, 179402.36 N, 151895.64 N, and 210867.69 N, respectively. The comparison of the results of an experimental program with the model proposed by several researchers shows that the equation proposed by Toutanji was close to the results of this experimental study. Based on this model, the equation was developed and modified to predict the axial strength of the reinforced concrete column strengthened with CFRP subjected to concentric loading was proposed in this article.

Keywords: R/C short column, Confinement, CFRP, Concentrically loaded, Modified equation

1. INTRODUCTION

Reinforcement of reinforced concrete columns is often required when a building undergoes a change in function that results in load demands exceeding the original design capacity. In such situations, structural strengthening is necessary to maintain safety, performance, and serviceability. One widely adopted strengthening technique is the jacketing method, which enhances the load-carrying capacity of columns by providing additional confinement and improving structural integrity. Among the materials used in jacketing systems, Fiber Reinforced Polymer (FRP) has gained significant popularity because of its high strength-to-weight ratio, corrosion resistance, durability, and ease of application. Common types of FRP used for structural reinforcement include Carbon Fiber Reinforced Polymer (CFRP), Aramid Fiber Reinforced Polymer (AFRP), and Glass Fiber Reinforced Polymer (GFRP).

Numerous studies have investigated the effectiveness of FRP for strengthening reinforced concrete columns [1-8]. These studies consistently demonstrate that CFRP confinement can significantly improve the strength and performance of reinforced concrete columns. Similarly, Wang et al. [9] conducted an experimental study on CFRP-coated reinforced concrete columns and reported

substantial increases in column strength due to confinement effects. These findings confirm the efficiency of FRP materials in enhancing structural performance.

Reinforced concrete columns can be constructed with circular or square cross-sections, and column geometry plays an important role in confinement effectiveness. Toutanji et al. [1] investigated FRP application in square columns using two layers of GFRP wrapping. In contrast, Wu and Wang [10] studied the retrofitting of circular columns with FRP and introduced the geometric parameter expressed as the angle ratio $2r/b$, with values ranging between zero and one. Although these studies provide important insights into confinement behavior, they are limited in terms of layer configuration and loading conditions.

The research of Toutanji et al. [1] focused on GFRP confinement limited to two layers, leaving uncertainty regarding the performance of columns strengthened with three layers of FRP. Therefore, further investigation is required to evaluate the strength of reinforced concrete short columns strengthened with three layers of CFRP. Lisantono and Pinang [11] examined CFRP-confined short columns subjected to eccentric loading, while Widiarsa and Hadi [12] also studied square columns strengthened with CFRP under eccentric loading conditions. Papakonstantinou [13] investigated

CFRP-confined reinforced concrete columns with rounded cross-sections. However, research specifically addressing square reinforced concrete short columns confined with CFRP and subjected to concentric loading remains limited.

Manoj and Sathyan [14] investigated square column strengthening using FRP composites consisting of synthetic carbon fiber and natural banana fiber, reporting improvements in axial load capacity, load-deformation behavior, and ductility. Dakhil et al. [15] conducted an experimental study on square reinforced concrete short columns strengthened with CFRP and found that ultimate load capacity increased by 30% to 90% compared with unconfined columns. However, their work did not develop a predictive equation for estimating column strength. Pati [16] also conducted experimental research on CFRP-strengthened short columns under concentric loading and compared the results with existing models, but no predictive formulation was proposed. This study develops and proposes an equation to predict the axial compressive strength of reinforced concrete columns strengthened with CFRP under concentric loading. By addressing this research gap, the study aims to enhance structural safety and resilience while contributing to both theoretical understanding and practical applications in structural engineering.

2. RESEARCH SIGNIFICANCE

This study offers a novel experimental and analytical contribution to the understanding of axial behavior of CFRP-confined reinforced concrete short columns under concentric loading. Unlike prior research that mainly validates existing confinement models, this work systematically examines layer-dependent strengthening effects using consistent specimen geometry and directly links cylinder and column responses. A key originality lies in developing and modifying a predictive equation calibrated with experimental evidence and validated against established models. The findings clarify non-linear strength enhancement trends and provide a refined design-oriented formulation, advancing reliability in assessing CFRP confinement efficiency for practical structural strengthening applications in real-world engineering practice.

3. MATERIALS AND METHODS

Concrete materials were taken from local materials. Fine aggregates were taken from the Krasak River, which is in the northern part of the Special Province of Yogyakarta, Indonesia. While the coarse aggregates were taken from Clereng, Kulonprogo, which is in the western part of the Special Province of Yogyakarta, Indonesia. The

concrete mixed design made in this research can be seen in Table 1.

Table 1 The concrete mixed design per 1 m³

| Material | Weight (kg) |
|-------------------|-------------|
| Portland Cement | 476 |
| Water | 233 |
| Fine aggregates | 805 |
| Coarse aggregates | 984 |

Mechanical properties of fine and coarse aggregates were tested before making the mixed design of concrete. Thirty-six-cylinder specimens were made with a size of 300 mm × 150 mm. The cylindrical specimens were made in four variations: nine cylinders without wrapping with Carbon Fiber Reinforced Polymer (CFRP); nine cylinders wrapped in one layer of Carbon Fiber Reinforced Polymer (CFRP); nine cylinders wrapped with two layers of Carbon Fiber Reinforced Polymer (CFRP), and nine cylinders wrapped with three layers of Carbon Fiber Reinforced Polymer (CFRP). All the cylinder specimens were tested in 7 days, 14 days, and 28 days to get the compressive strength of concrete. The tensile strength of the steel bar was also tested to determine the yield stress of the steel bar.

Four specimens with a size of 75 mm × 75 mm × 750 mm were made and tested in this research. One specimen was the column without CFRP as a reference specimen, while the others were confined with one, two, and three layers of CFRP, respectively. The fiber direction of the CFRP was installed perpendicular to the longitudinal axis of the column. The supports of the column were fixed support. So, the slenderness ratio of the column (KL/r) was 17.32. This column can be classified as short column. All of cylinder and column specimens were cured in the room temperature.

The CFRP had the properties of a tensile modulus of 230,000 MPa, a tensile strength of 4,900 MPa, and a maximum strain was 1.7%. The dry thickness of CFRP is 0.129 mm per layer. The installation of the CFRP first the surface of the column was made roughly and then greased with a mixture of Epoxy. After greasing with Epoxy, the installation of CFRP can be done. Three days after the installation of CFRP, the column specimens were ready to be tested.

3.1 Set-up Testing

The Column specimen was placed in the loading frame in a horizontal position. At the position of the test object lying down, the self-weight of the test object was ignored because the effect of its own weight was very small. The column was given a concentric load using a hydraulic jack, as shown in

Fig. 1. The load was monotonic loading with the loading rate was 0.5 inch per minute.



Fig. 1 Set-up of column test specimens

The placement of the LVDT is in the middle of the span, with its placement in horizontal and vertical directions, which can be seen in Fig. 1. The installation of the LVDT in the middle of the span is also intended to determine whether there is a deviation in the transverse direction. In the test mechanism, the column is subjected to an axial force until the column fails. The data to be observed in the form of load data provided by a hydraulic jack and deflection data by LVDT computerized using a data logger, as shown in Fig. 2.



Fig. 2 Column testing

4. RESULTS AND DISCUSSION

4.1 Concrete compressive strength

The results of the 28-day concrete compressive strength testing can be seen in Table 2. Table 2 shows that the compressive strength of cylinder concrete at the age of 28 days has increased with the increase in the layer of CFRP. The cylinder specimen that was strengthened with one layer of CFRP, the compressive strength increased by 18.54% compared to the compressive strength of the cylinder concrete without CFRP. The

compressive strength of cylinder concrete strengthened with two layers of CFRP increased by 21.71% compared to the compressive strength of concrete without CFRP. While the cylindrical specimen strengthened with three layers of CFRP, the compressive strength of concrete increased by 26.94% compared to the compressive strength of concrete without CFRP. It can be said that increasing the layers of CFRP in cylinder specimens with one layer, two layers and three layers significantly increases the compressive strength of concrete.

Table 2 The compressive strength of concrete at 28 days.

| Specimen code | Compressive strength (MPa) |
|---------------|----------------------------|
| SP TL | 22.03 |
| SP L1 | 32.06 |
| SP L2 | 34.25 |
| SP L3 | 38.27 |

Note: SP TL = Cylinder specimen without CFRP; SP L1 = Cylinder specimen with one layer of CFRP; SP L2 = Cylinder specimen with two layers of CFRP; and SP L3 = Cylinder specimen with three layers of CFRP.

4.2 Crack Pattern

The crack pattern of the column specimen can be seen in Fig.3. Generally, the cracks started near to the edge of the column. With increasing the load, the width of these cracks increased slowly, and new cracks developed and began to propagate generally towards the middle and the edges of the column.



Fig. 3 Crack pattern of the column specimen

4.3 The load capacity of the column

The maximum load capacity of the column subjected to concentric load can be seen in Table 3. Table 3 shows the maximum load capacity for each variation of the column specimen. It can be seen from Table 3 that the maximum load capacity of the column increased when the number of layers of CFRP also increased. Except for column K2, the maximum load value is smaller than column K1 due

to poor casting of the column, resulting in cavities (porous) in the column, which results in a reduction in the strength of the column.

Table 3 The maximum load capacity of the column

| Specimens Code | Maximum Load (N) |
|----------------|------------------|
| K0 | 121372.12 |
| K1 | 179402.36 |
| K2 | 151895.62 |
| K3 | 210867.69 |

Note: K0 = Column without CFRP as control specimen; K1 = Column strengthening with one layer of CFRP; K2 = Column strengthening with two layers of CFRP; and K3 = Column strengthening with three layers of CFRP.

The column specimen, which was strengthened with one layer of CFRP, showed an axial load capacity increase of 19.29% compared to column specimens without CFRP. The axial load capacity of the column strengthened with two layers of CFRP increased 11.17% compared to the column specimen without CFRP. While the column strengthened with three layers of CFRP, the load capacity increased 26.94% compared to column specimens without CFRP. It can be concluded that increasing the layers of CFRP will increase the load capacity of the column.

4.4 The comparison of the experimental test results with the model proposed by other researchers

The equation or model proposed by Toutanji et al. [1] is as follows (Eq. (1)):

$$\frac{f'_{cc}}{f'_{co}} = 1 + k_1 k_2 k_3 \frac{f'_l}{f'_{co}} \quad (1)$$

with,

f'_{cc} = compressive strength of the confined concrete cylinder

f'_l = radial confinement stress in concrete

f'_{co} = the unconfined concrete cylinder compressive strength

Where the coefficients k_2 and k_3 are taken into account from the various radii and aspect ratio angles of each:

$$k_2 = \left[\frac{2r}{D}\right]^\alpha \text{ and } k_3 = \left[\frac{d}{D}\right]^\beta \quad (2)$$

The values of α and β in Eq. (2) are taken at 0.10 and 0.12, respectively, while for k_1 is taken at 4.0 [1].

Rectangular lateral effective pressure by FRP (f'_l), is:

$$f'_l = k_e f_l \quad (3)$$

The coefficient of k_e is determined by equation as follows:

$$k_e = \frac{1 - (((h-2r)^2 + (b-2r)^2) / 3A_g) - \rho_{sc}}{1 - \rho_{sc}} \quad (4)$$

with:

A_g = gross cross-sectional area of concrete

ρ_{sc} = area of steel to gross cross-sectional area of concrete

r = radius of the corners

The maximum FRP pressure in the confined column is determined by the following equation:

$$f_l = \frac{2 E_{FRP} n t_j \epsilon_j}{D} \quad (5)$$

with,

E_{FRP} = the tensile modulus of elasticity of FRP

n = the number of FRP layer

t_j = the FRP thickness, and ϵ_j is FRP lateral strain with:

$$\epsilon_j = 0.43 \epsilon_{FRP} \quad (6)$$

with a column diameter of:

$$D = \frac{2bh}{b+h} \quad (7)$$

The equation or model proposed by Lam and Teng [17] is:

$$\frac{f'_{cc}}{f'_{co}} = 1 + 3.3 \left(\frac{A_e}{A_c}\right) \left(\frac{f_l}{f'_{co}}\right) \quad (8)$$

with,

$$\frac{A_e}{A_c} = 1 - \frac{(b/h)(h-2r)^2 + (h/b)(b-2r)^2}{3A_g(1-\rho_g)} \quad (9)$$

where A_g is the gross area of the column:

$$A_g = bh - (4 - \pi)r^2 \quad (10)$$

The equation or model proposed by Campione and Miraglia's [18] is as follows:

$$\begin{aligned} \frac{f'_{cc}}{f'_{co}} &= 1 + 2.0 k_s \left(\frac{f_l}{f'_{co}}\right) \\ &= 1 + 2.0 k_s \left[0.85 \left(\frac{2r}{b}\right) + 0.15\right] \left(\frac{2t}{b}\right) \left(\frac{f_{FRP}}{f'_{co}}\right) \end{aligned} \quad (11)$$

with,

f'_{cc} = compressive strength of the confined concrete cylinder

f'_l = radial confinement stress in concrete

f'_{co} = the unconfined concrete cylinder compressive strength

The model proposed by Kumutha et al. [19] is given in the following equation as:

$$\frac{f'_{cc}}{f'_{co}} = 1 + 0.93 \left(\frac{f_l}{f'_{co}} \right) \quad (12)$$

with,

f'_{cc} = compressive strength of the confined concrete cylinder

f_l = radial confinement stress in concrete

f'_{co} = the unconfined concrete cylinder compressive strength

The comparison between the experimental test results and the model proposed by Toutanji et al. [1]; Lam and Teng [17]; Campione and Miraglia's [18]; and Kumutha et al. [19] can be seen in Table 4.

Table 4 shows that the difference between the test results of column K1 and the model of Toutanji et al. [1] was 0.51%. The difference between the test results of column K2 and the model of Toutanji et al. [1] that is 21.15%. Meanwhile, the difference between the results of the K3 column test and the Toutanji et al. [1] was 2.05%.

The difference between the test results of column K1 and Lam and Teng's [17] model is 14.69%. The difference between the results of the K2 column test with the Lam and Teng's [17] model is 39.86%. While the difference between the results of the K3 column test with the Lam and Teng's [17] model is 30.90%.

The difference between the test results of column K1 with Campione and Miraglia's [18] model is 16.78%. The difference in the test results of the K2 column with Campione and Miraglia's [18] model is 42.27%. While the difference between the results of the K3 column test with Campione and Miraglia's [18] model is 34.31%.

While the difference between the test results of column K1 and the model Kumutha et al. [19] amounted to 10.61%. The difference between the test results of column K2 and the model of Kumutha et al. [19] amounted to 44.59%. Meanwhile, the difference between the results of the K3 column test and the Kumutha et al. [19] amounted to 47.10%.

The results of the comparison above show that the equation of Toutanji et al. [1] have the smallest difference, namely for K1 of 0.26%, for K2 of 11.83%, and for K3 of 1.04%. Thus, the verification results show that the model or equation proposed by Toutanji et al. [1] is an equation or model that

approximates the experimental results for reinforced concrete short columns with CFRP restraints.

4.5 The Development Equation for Predicting the Axial Compressive Strength of Column

Looking at the results of a study conducted by Pati [16], the equation that is close to the experimental results for short reinforced concrete columns restrained by CFRP and subjected to concentric load is the equation proposed by Toutanji et al. [1]. So in this article, an equation will be developed to predict the compressive strength of a short column of reinforced concrete that is restrained by CFRP, which is subjected to concentric loads based on this equation.

Based on the previous discussion, the compressive strength of K2 column was lower than K1 column because of the poor casting. This results in the unusual trend of the confinement effect ratio. Comparing the compressive strength ratio of columns and cylindrical samples, as shown in Table 4, enlighten which ratios can be the references for the proposed equation. From Table 5, the confinement effect ratio of K1 and K3 columns are very close to the ratio in cylindrical samples (SP L1 and SP L3). It indicates a coherent relationship between columns and cylinders confinement effect ratio. Therefore, the use of the confinement effect ratio of the cylinder is reasonable as a reference to the proposed equation.

The development of the column compressive strength prediction equation is based on Eq. (1) because it has the closest gap with the experimental result in this study, as shown in Table 4. However, the different shapes of the corner columns require some modifications in the equation. The first modification is the determination of the k_2 value to become one because of the non-rounded corners in the present study. Secondly, the value of k_e , which is the coefficient of the area efficiency should also accommodate the no-roundness corner condition. In this calculation (Eq. (9)), the variable r equals to zero, so the equation becomes Eq. (13):

$$k_e = \frac{1 - 2bh/3A_g - \rho_{sc}}{1 - \rho_{sc}} \quad (13)$$

Table 4 The comparison between the experimental test results and the model proposed

| Column type | Experiment (N) | Tautanji et al. Model (N) | Lam dan Teng Model (N) | Campione dan Miraglia's Model (N) | Kumutha <i>et al</i> Model (N) |
|-------------|----------------|---------------------------|------------------------|-----------------------------------|--------------------------------|
| K1 | 179402.36 | 180326.80 | 210286.14 | 215569.34 | 200700.78 |
| K2 | 151895.64 | 192638.85 | 252557.52 | 263123.93 | 274134.74 |
| K3 | 210867.69 | 215280.85 | 305158.86 | 321008.47 | 398646.62 |

Table 5 Comparison between columns and cylinders confinement effect ratio

| Column | Cylinder | Error (%) |
|------------|------------------|-----------|
| K1/K0 1.48 | SP L1/SP TL 1.46 | 1.54 |
| K2/K0 1.25 | SP L2/SP TL 1.55 | 24.23 |
| K3/K0 1.74 | SP L3/SP TL 1.74 | 0.01 |

The last modification is the coefficient of the effective strain in CFRP reinforcement obtained at failure. Toutanji et al. [1] used 0.43 as the efficiency factor (Eq. (6)). However, ACI 440.2R-17 [20] mentioned several different numbers based on experimental calibration. In this study, using the trial and improvement method, the proposed efficiency factor was observed so that the confinement effect ratio of the theoretical calculation coincides with the confinement effect ratio of the cylinder samples. The method began with the use of [1] which results in a high error compared with the cylinder's confinement effect ratio. Continuing the method with the values of 0.21, 0.22, and 0.23 yields the closer results as shown in Tables 6, 7, and 8.

Table 6 Comparison between the cylinders confinement effect ratio and the proposed equation with $\epsilon_j = 0.21\epsilon_{FRP}$

| SP-L/SP-TL | Proposed Equation | Error |
|------------|-------------------|--------|
| 1.46 | 1.31 | 11.0% |
| 1.55 | 1.62 | -4.1% |
| 1.74 | 1.93 | -10.1% |

Table 7 Comparison between the cylinders confinement effect ratio and the proposed equation with $\epsilon_j = 0.22\epsilon_{FRP}$

| SP-L/SP-TL | Proposed Equation | Error |
|------------|-------------------|--------|
| 1.46 | 1.33 | 9.8% |
| 1.55 | 1.65 | -5.8% |
| 1.74 | 1.98 | -12.1% |

Table 8 Comparison between cylinders confinement effect ratio and proposed equation with $\epsilon_j = 0.23\epsilon_{FRP}$

| SP-L/SP-TL | Proposed Equation | Error |
|------------|-------------------|--------|
| 1.46 | 1.34 | 8.6% |
| 1.55 | 1.68 | -7.5% |
| 1.74 | 2.02 | -14.0% |

Based on the error comparison of Table 6, 7, and 8, it is found that the coefficient of the effective strain in CFRP reinforcement is 0.22. Thus, the proposed strength prediction equation in this study consists of the calculation of the effective strain coefficient as follows:

$$\epsilon_j = 0.22\epsilon_{FRP} \quad (14)$$

5. CONCLUSION

Based on the results of experimental tests, the following conclusions can be drawn:

Confinement with CFRP significantly increases the axial compressive strength of concentrically loaded reinforced concrete short columns.

The comparison between the experimental test results and several models shows that the equation proposed by Toutanji et al. [1] has the smallest difference. Thus, the verification results show that the equation proposed by Toutanji et al. [1] is an equation or model that is close to the experimental test results in this study.

The proposed strength prediction equation for a column with no-rounded corners is developed based on the Toutanji [1] equation. The modifications needed are $k_2 = 1$, the calculation of k_e that follows Eq. (13), and the use of 0.22 for the efficiency factor (see Eq. (14)).

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