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The Effect of Confining Using Carbon Fiber Reinforced Polymer (CFRP) on the Characteristics of the Stress-Strain Relationship of Round Columns in Concrete Retrofit Systems

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Abstract

Columns are structural parts whose main function is to resist compressive axial forces. From the results of studies, it is shown that confined concrete parts will increase their ability to withstand compressive axial forces. This research aims to examine the characteristics of the stress-strain relationship in round columns confined with CFRP in a column retrofit system. A total of three short columns with a diameter of 175 mm and a column length of 875 mm were tested with a monotonic axial load until they failed. One column without CFRP restraint and 2 consecutive columns restrained with 1-layer and 2-layer CFRP. From the research results it was shown that the column compressive strength increased by 54.6% for 1-layer CFRP restraint and 106.2% for 2-layer CFRP restraint. The stress coefficient k1 value ranges from 2.9 to 3.2 and the strain coefficient k2 value ranges from 19.4 to 24.3. It does not matter with the different ranges of k1 and k2 because k1 and k2 are coefficients of 2 different parameters, namely k1 is the stress coefficient while k2 is the strain coefficient. This value is almost the same as the results of previous research, namely k1 = 4.1 and k2 = 20.5 for columns confined with ordinary reinforcement.

1. Introduction

Errors in planning or deviations in the construction of a building often occur, so an appropriate way is needed to overcome this. Many repair or strengthening methods have been developed to overcome this. However, of the many methods, the most popular is the reinforcement method using Carbon Fiber Reinforced Polymer (CFRP) because it has many advantages, including lightweight, high tensile strength, durability, and corrosion resistance[1][2]. Columns are structural elements that have a very important role when compared to other structural elements. A structure will collapse if its columns collapse. Therefore, if after evaluation it is proven that there is a vulnerability, the structural parts that must be strengthened first are the columns. Columns will be strengthened if increasing the number or enlarging the columns is no longer possible due to spatial and architectural concepts. Several studies have been carried out on columns reinforced with CFRP, but they are still limited to the contribution of CFRP to strength. Meanwhile, the characteristics of the stress-strain relationship of reinforced concrete confined with CFRP have not been widely studied, especially for round columns.

When viewed in terms of material strength, CFRP has a tensile strength 10 times greater than reinforcing steel. However, its properties and behavior when combined with reinforced concrete as reinforcement under certain loads still need to be studied because it is already a composite material with concrete. On the other hand, a column is a structural part whose main function is to resist compressive axial forces. From the results of previous research, it has been shown that confined concrete parts will increase their ability to withstand compressive axial forces[2]–[4]. The specific objectives of this research are: (a) Investigate the contribution of restraint using CFRP material in a round column strengthening system. (b) Determine the characteristics of the stress-strain relationship in round columns confined with CFRP in a round-column reinforcement system.

1.1 Carbon Fiber Reinforced Polymer (CFRP)

CFRP is the result of current material technology innovation, where the production process requires strict supervision, namely by extruding a polymer with a carbonization process at temperatures between 350oC – 1600oC. With its superior properties, including tensile strength 10 times greater than steel, lightweight, and corrosion resistance, it is not excessive if CFRP is used as an alternative to the main material for strengthening structures[1]. When compared with reinforcing steel, CFRP has many advantages, for example, tensile strength which can be up to 10 times greater; density 10 times smaller; excellent fatigue characteristics that can reach 3 times greater; corrosion resistance; not affected by electromagnetic fields; and low coefficient of expansion.

Figure 1 provides information about CFRP material when compared with other types of reinforcement materials.

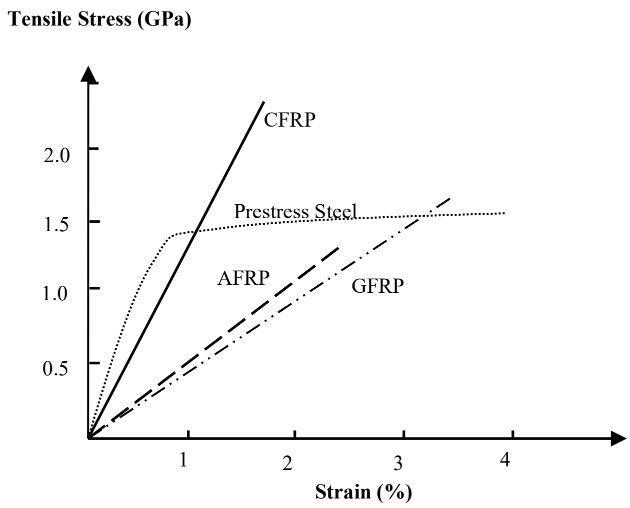


Fig. 1 *Characteristics of CFRP materials and other materials*

Annotation:

CFRP = Carbon fiber reinforced polymer. CFRP is a polymer material for reinforcement made from carbon fibers.

AFRP = Aramid fiber reinforced polymer. AFRP is a polymer material for reinforcement made from aramid fibers.

GFRP = Glass fiber reinforced polymer. GFRP is a polymer material for reinforcement made from glass fibers.

1.1 Confinement with CFRP

From research by Seibel & Karbhari[5], [6], obtained the following formulation: The stress that CFRP can withstand is

$$f_l = \frac{2f_{Lu}.t_L}{D} \tag{1}$$

where f_{Lu} is the ultimate stress that can be withstood by concrete and CFRP, t_L is the estimated CFRP thickness requirement, and D is the column diameter.

The estimated ultimate strain that can be withstood by concrete and CFRP is

$$\varepsilon_{cu} = 0{,}004 + \frac{2{,}8.\rho_L.\varphi_F.f_{LU}.\varepsilon_{Lu}}{f'_{cc}} \tag{2}$$

Where:

$$\rho_L = \frac{4.t_L}{D} \text{ and } \varphi_F = 0{,}9 \tag{3}$$

The estimated CFRP thickness requirement:
for round cross-section

$$t_L = \frac{0{,}09.(\varepsilon_{cu} - 0{,}004).D.f'_{cc}}{\varphi_F.f_{Lu}.\varepsilon_{Lu}} \quad (4)$$

for a square cross-section

$$t_L = \frac{0{,}18.(\varepsilon_{cu} - 0{,}004).D.f'_{cc}}{\varphi_F.f_{Lu}.\varepsilon_{Lu}} \quad (5)$$

Meanwhile, from the results of Mander & Priestley's research[4] on round columns confined with spiral reinforcement, a force balance can be formulated:

$$2.f_y.A_{sp} = D.s.f_l \quad (6)$$

where: fy is the yield stress of the steel, Asp is the cross-sectional area of the spiral stirrups, D is the diameter of the column, s is spacing of the stirrups, and f_l is the lateral stress in the concrete. Based on equations 1 - 6, for confinement with CFRP applies:

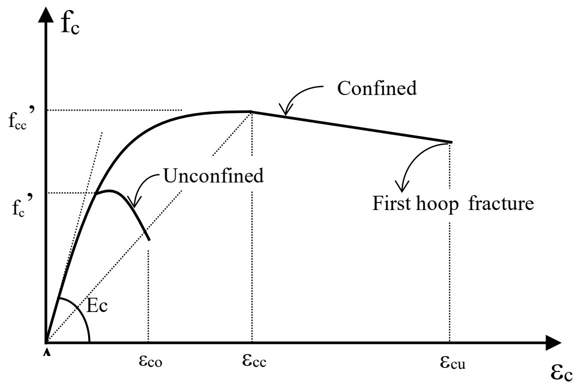
$$2f_{Lu}.A_L = D.s.f_l \quad \text{then} \quad 2f_{Lu}.s.t_L = D.s.f_l \quad \text{then} \quad 2f_{Lu}.t_L = D.f_l \quad \text{so that} \quad f_l = \frac{2f_{Lu}.t_L}{D} \quad (7)$$

$$f'_l = k_e.f_l \quad (8)$$

and

$$k_e = \frac{A_e}{A_{cc}} \quad (9)$$

where f_l' is the effective lateral stress; *Ae* is the effective area of the concrete core confined within the spalling line,



and *Acc* is the effective area of the concrete core confined outside the spalling line.

Fig. 2 *Stress-strain relationship curves for confined and unconfined columns*

For spiral stirrups the value is equal to 0.95 (Park & Paulay, 1975), and for restraints with CFRP it is clear that the value *Ae = Acc*, so the value of k_e is equal to 1. Figure 2 shows the relationship between stress and strain for confined and unconfined concrete where fc' is the characteristic stress of unconfined concrete and fcc' is the characteristic stress of confined concrete. This relationship is formulated in equations 10 to 16.
The maximum compressive stress in confined concrete is:

$$f'_{cc} = \left(-1{,}254 + 2{,}254.\sqrt{1 + \frac{7{,}94.f'_l}{f'_c}} - \frac{2.f'_l}{f'_c}\right).f'_c \quad (10)$$

where *fc'* is the characteristic stress of concrete. The strain value when the fcc' maximum stress occurs

$$\varepsilon_{cc} = 0{,}002.\left(1 + 5.\left(\frac{f'_{cc}}{f'_c} - 1\right)\right) \quad (11)$$

Meanwhile, the modulus of elasticity of confined concrete when maximum stress occurs is:

$$Esec = \frac{f'_{cc}}{\varepsilon_{cc}} \tag{12}$$

The modulus of elasticity of concrete is:

$$E_c = 4730.\sqrt{f'_c} \tag{13}$$

The ratio of the modulus of elasticity between unconfined concrete and confined concrete is:

$$r = \frac{E_c}{E_c - E_{sec}} \tag{14}$$

The ratio between the concrete strain that occurs ε_c and the strain when the maximum stress

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}} \tag{15}$$

Thus the stress-strain relationship for confined concrete can be written[7], [8] as

$$f_c{}' = \frac{f'_{cc}.x.r}{r - 1 + x^r} \tag{16}$$

1.2 Confined Concrete Stress-Strain Relationship Model

Previous research results [7]–[10] show that the stress-strain relationship in confined concrete can be presented simply in the equations:

$$f'_{cc} = f'_c + k_1.f_l \tag{17}$$

and

$$\varepsilon_{cc} = \varepsilon_c\left(1 + k_2\frac{f_l}{f'_c}\right) \tag{18}$$

where ***fcc'*** is the maximum compressive stress of confined concrete, ε_{cc} is the maximum strain confined concrete, ***fc'*** is the characteristic stress of concrete without restraint, ε_c is the maximum strain of concrete without restraint, f_L is the lateral stress in confined concrete and ***k1, k2*** are stress and strain coefficients. Research conducted by Richard (1928) (in Mander, 1984) [7], [10], on confined concrete obtained values of k_1 = 4.1 and k_2 = 5.k_1. Likewise, Balmer (1949) (in Mander, 1984)[4], [7], [10] gives a value of k_1 varying between 4.5 to 7. And finally, Mander (1984) gives a value of k_1 = 5.

2. Method

This research is an experimental study aimed at investigating the characteristics of the stress-strain relationship of round columns confined with CFRP with three variations number of layers of CFRP as an independent variable, namely zero (0), one (1), and two (2) layers of CFRP. The dependent variables are the stress and strain coefficient values k1 and k2 from equations 17 and 18.

2.1 Test Object Specifications

The total number of column test specimens is 3 with the following specifications: concrete compressive strength fc' = 22.18 MPa, steel tensile strength fy = 436.33 MPa, longitudinal reinforcement ratio ρ = 2.26%, concrete cover thickness 40 mm, and stirrup diameter ϕ 7.25 – 172 mm. Complete specifications for column test specimens can be seen in Table 1.

Table 1 *Specifications of column test specimens*

Column Code	Dia.	Height	Longitudinal reinforcement		Transversal reinforcement		CFRP
	(mm)	(mm)	∅ (mm)	∑ (bh)	∅ (mm)	Spacing (mm)	t = 0,13 (Layers)
K1-Wo	175	875	10,75	6	7,25	172	0
K1-W1	175	875	10,75	6	7,25	172	1
K1-W2	175	875	10,75	6	7,25	172	2

while typical images of reinforcement and CFRP placement can be seen in Figure 3. Figure 3 shows the CFRP installation process. For CFRP installation that exceeds one layer around a column, the minimum overlap that must be used is 100 mm.

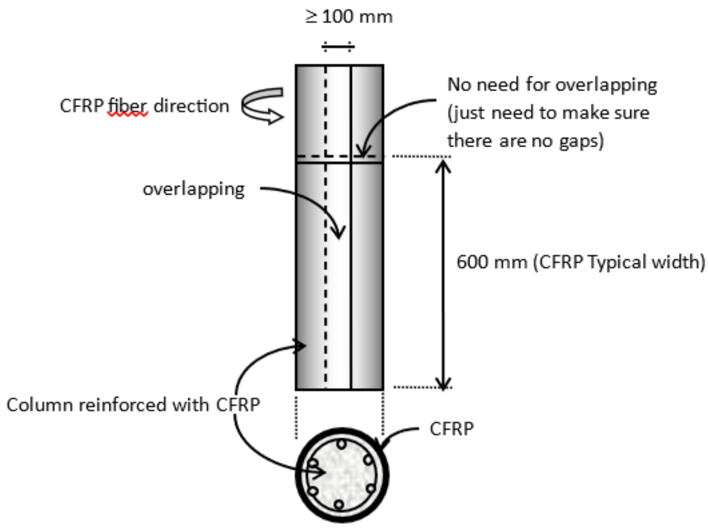


Fig. 3 *Overlapping on CFRP installation*

The CFRP installation process is the most important part of the work and requires high precision. The first thing to do is to prepare the concrete surface so that it reaches a minimum contact stress of 1.5 N/mm2. This condition can be achieved by cleaning the concrete surface with a mechanical brush so that the soft parts of the concrete surface can be removed. If necessary, concrete surface repair with Sikadur 41 can be used. Once this stage has been completed, you can proceed with attaching the CFRP to the concrete surface. For CFRP installation that exceeds one layer, the minimum overlap that must be used is 100 mm. Figure 3 describes a typical CFRP installation[11]. The CFRP used is the Wrap type with the dimensions of each roll being 0.13 mm thick, 610 mm wide, and ⍰ 45 m long. Other specifications [12] can be seen in Table 2.

Table 2 *Specific specifications of CFRP*

No.		Values
1.	Yield tensile strength	3500 N/mm2
2.	Modulus of elasticity	230000 N/mm2
3.	Elongation of rupture	1,5 %
4.	Specific gravity	225 gram/m2
5.	Life time	unlimited

2.2 Testing of Column Specimens

Before the column axial load test, CFRP was first installed on the column test specimens. The CFRP installation process is the most important part of the work and requires high precision. The first thing to do is to prepare the concrete surface so that it reaches a minimum contact stress of 1.5 N/mm2, this condition can be achieved by cleaning the concrete surface with a mechanical brush so that the soft concrete surface can be removed, if necessary, concrete surface repair can be used with Sikadur 41. After this stage is perfectly done, it can be continued with attaching the CFRP to the concrete surface. For CFRP installation that exceeds one layer, the minimum overlap that must be used is 100 mm. Figure 3 explains the typical installation of CFRP.

The strain that occurs is measured with a strain gauge at several points which are then connected to a data logger. To ensure the condition of the strain gauge is in good condition, before and after installing the strain gauge the condition must be checked again. In this case, it is recommended to use an AVO meter. A schematic of the location of the strain gauge installation can be seen in Figure 4. Next, the column test object was tested with axial load using a universal testing machine (UTM) with a capacity of 200 tons. Loading speed using strain rate of 0.1mm/min.

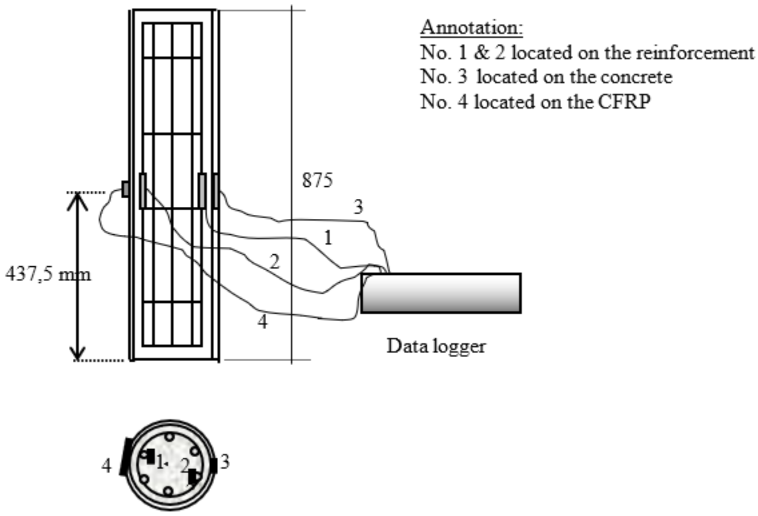


Fig. 4 *The strain gauge installation*

3. Results and Discussion

3.1 Test Object Specification

The theoretical results of the analysis of the maximum axial force and strain that occur in the test object are shown in Table 3.

Table 3 *Results of theoretical prediction analysis of test objects*

Column' Number	Ag	As	⍰	fc'	fy	Layers of CFRP	f_{Lu}	P_{max}	⍰P_{max}
1	2	3	4	5	6	7	8	9	10
K1-W0	24052,819	544.575	2,26	22,18	436,33	0	3500	60,700	0,0020
K1-W1	24052,819	544.575	2,26	22,18	436,33	1	3500	102,834	0,0120
K1-W2	24052,819	544.575	2,26	22,18	436,33	2	3500	142,365	0,0200

3.2 Analytical Stress-Strain Diagrams

Figure 5 shows the value of the combined stress-strain relationship between concrete and reinforcement before being confined analytically, while after experiencing confinement with CFRP the characteristics of the stress-strain relationship are shown in Figure 6. It can be seen that analytically, the increase in compressive strength capacity will occur quite large between before restraint and after restraint.

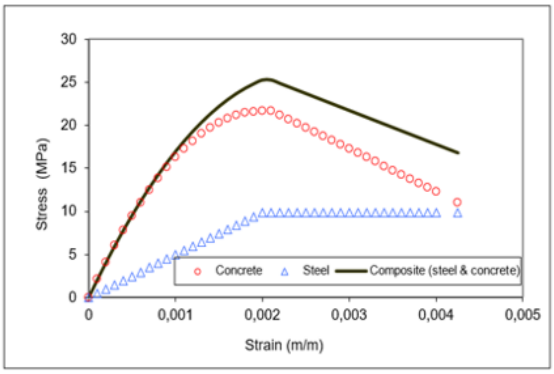


Fig. 5 *Analytical stress-strain relationship curve for reinforced concrete*

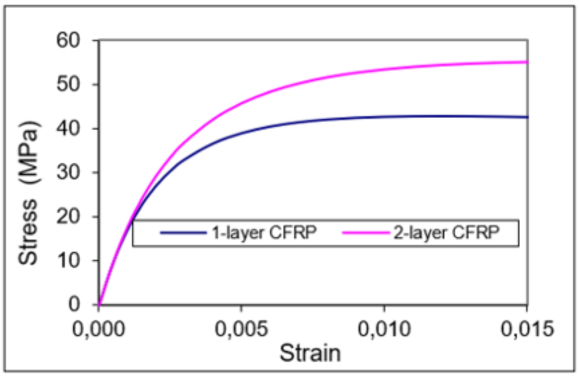


Fig. 6 *Analytical stress-strain relationship curve for CFRP column*

3.3 Experimental Stress-Strain Diagram

Figure 7 shows the results of the tensile test of the reinforcement which generally has the properties and behavior of steel reinforcement in general. From the test results, the yield strain and yield stress values were 0.002 and 436.3 MPa. Meanwhile, Figure 8 shows the tensile test results of CFRP material with the maximum tensile stress obtained being 3500 MPa while the maximum strain is 0.016.

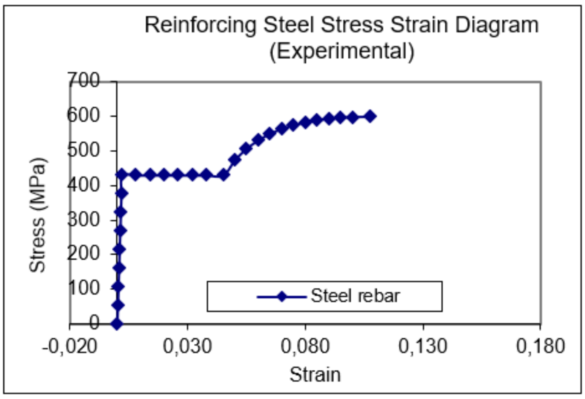


Fig. 7 *Reinforcing steel stress-strain relationship curve (Material tensile test results)*

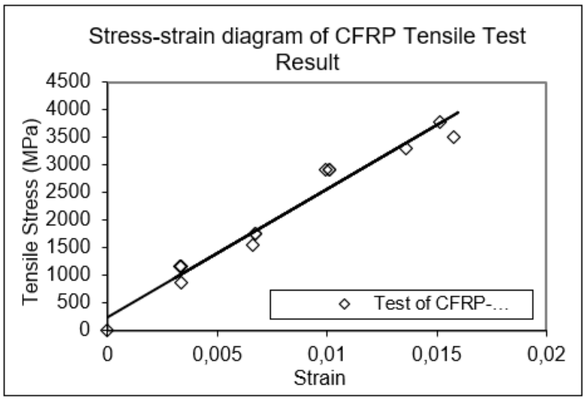


Fig. 8 *CFRP stress-strain relationship curve (Material tensile test results)*

From the test results, the stress-strain relationships of columns in each condition, namely columns without restraints, columns restrained by one layer of CFRP, and columns restrained by two layers of CFRP can be shown in Figure 9. The differences that occur between each treatment are also shown. The difference in maximum stress or strain values that occur is very visible, this proves that confinement in columns using CFRP has a large contribution to increasing capacity[13]–[15].

3.4 Analytical and Experimental Comparison of Column Capacity

Experimentally, it can be seen that the increase in column capacity from normal columns to columns restrained by 1-layer and 2-layer CFRP (Figure 9) shows a linearly proportional relationship, namely that there is an average increase of: $\frac{(54,62\% + 106,16\%)}{3} = 53,59\%$ for each layer of restraint using CFRP

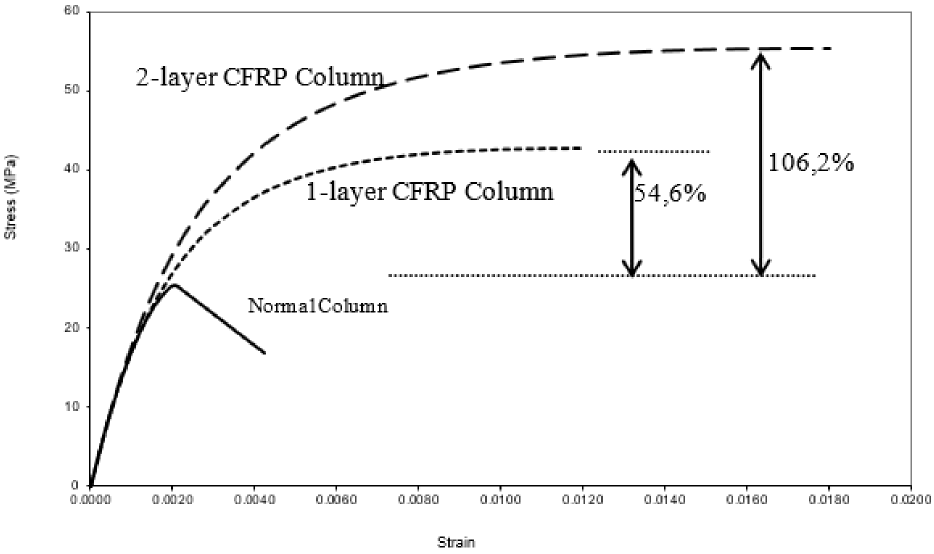


Fig. 9 *Comparison of stress-strain diagrams between normal columns, confined by 1 layer CFRP and confined by 2 layers CFRP and their increased capacity*

Table 4 *Column strength capacity*

Column number	Column type	Max. Analytical Stress (MPa)	Max. Experimental Stress (MPa)	Strength Enhancement By Analytical	Strength Enhancement By Experimental
K1-W0 (A)	Normal	25,289	27,037		
K1-W1 (B)	Restrained by 1 Layer CFRP	42,775	41,804	69,14% (B-A)/A	54,62% (B-A)/A
K1-W2 (C)	Restrained by 2 Layers of CFRP	55,373	55,739	118,96% (C-A)/A	106,16% (C-A)/A

3.5 Formulation of Stress-Strain Relationship Characteristics of CFRP Confined Columns

Determination of the value of k1 and k2, based on the basic restraint formula [4]: (see Equations 17 & 18) $f'_{cc} = f'_c + k_1 . f_l$ ...(17) and $\varepsilon_{cc} = \varepsilon_c \left(1 + k_2 \frac{f_l}{f'_c}\right)$ ...(18)

Table 5 *Values of k1 and k2 when compared with ordinary restraints*

Coefficient of restraint	According to Richard (1928) (in Mander, 1984)	According to Balmer (1949) (in Mander, 1984)	According to Mander (1984)	CFRP restrained 1 Layer	CFRP restrained 2 Layers
k1	4,1	4,5 to 7	5	3,18	2,93
k2	20,5	-	-	24,3	19,4

3.6 Application of CurveExpert Software to Determine Stress-Link Characteristics in CFRP Confined Columns

By entering the stress and strain values from the experimental results into the CurveExpert software and formatting the curve modeling according to the basic equation for the stress-strain relationship of confined concrete as follows [16]: (see Equation 16)

$$f_c = \frac{f'_{cc}.x.r}{r-1+x^r}$$ ...(16) then the coefficient values will be obtained as follows:

Table 6 *Comparison of maximum stress and strain values*

Parameters	CFRP confinement 1 Layer			CFRP confinement 2 Layers		
	Analytical	Eksp. & Software	% difference	Analytical	Eksp. & Software	% difference
fcc'	42,775	40,291	5,807	55,373	48,829	11,818
r	1,202	1,188	1,165	1,170	1,0173	13,077
εcc	0,012	0,0077	35,833	0,018	0,00994	45,167

If we look at the experimental results analyzed using the CurveExpert software for fcc' with 1-layer and 2-layer confinement, namely 40.291 MPa and 48.829 MPa respectively, the results are close to the analytical maximum stress, namely 42.775 MPa and 55.373 MPa. The percentage difference between analytical results and experimental results is 5.807% for a 1-layer confined column and 11.818% for a 2-layer confined column. Meanwhile, the ultimate strain (cc) of the experimental results for 1-layer and 2-layer restraints, namely 0.0077 and 0.00994, respectively. From the results of the ultimate strain calculation, the analysis results are 0.012 and 0.018 respectively. So the percentage difference between the analysis results and the experimental results for the ultimate strain is 35.833% for a 1-layer confined column and 45.167% for a 2-layer confined column. It can be concluded that determining characteristics using CurveExpert can be done with a small correction factor, especially for the fcc' and cc values, namely fcc' is reduced with a reduction factor of 0.94 for 1 layer of restraint and reduced with a reduction factor of 0.88 for 2 layers of restraint layers, while the strain value cc is reduced by a reduction factor of 0.64 for 1-layer restraints and reduced by a reduction factor of 0.55 for 2-layer restraints. This reduction factor is obtained from the equation: reduction factor = 1 - % difference for each parameter in each CFRP confinement in Table 6.

4. Conclusions And Recommendations

From the discussion of the research results, several important conclusions can be made as follows:

i. The results of analytical calculations and experimental tests show a close relationship or it can be said that the deviation is small. This proves the validity of the research methodology carried out[17].

ii. There was a very significant increase in the column capacity to withstand axial loads. The research results show that there will be an increase in capacity of 53.59% for each layer of restraint using CFRP.

iii. The stress coefficient k1 value ranges from 2.9 to 3.2 and the strain coefficient k2 value ranges from 19.4 to 24.3. It does not matter with the different ranges of k1 and k2 because k1 and k2 are coefficients of 2 different parameters, namely k1 is the stress coefficient while k2 is the strain coefficient. As a comparison for restraints using stirrups presented by Richard (1928) (in Mander (1988)) the values of k1 = 4.1 and k2 = 20.5.

iv. By using the CurveExpert software, the approach to formulating the characteristics of the stress-strain relationship will be closer to the experimental results. This means that the formulation presented by Mander et al., can be used but must be made a little correction, namely the maximum stress value (fcc') must be multiplied by a reduction factor of 0.88 to 0.94 and the maximum strain value (cc) must be multiplied by a reduction factor of 0 .55 to 0.64.

v. Referring to the radial direction CFRP stress-strain relationship curve, a column confined with 1 layer of CFRP will have more ductile properties compared to a column confined with 2 layers of CFRP, but on the other hand, the capacity to withstand axial loads is relatively smaller.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of this paper.

Author Contribution

The authors confirm contribution equally to the paper.

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