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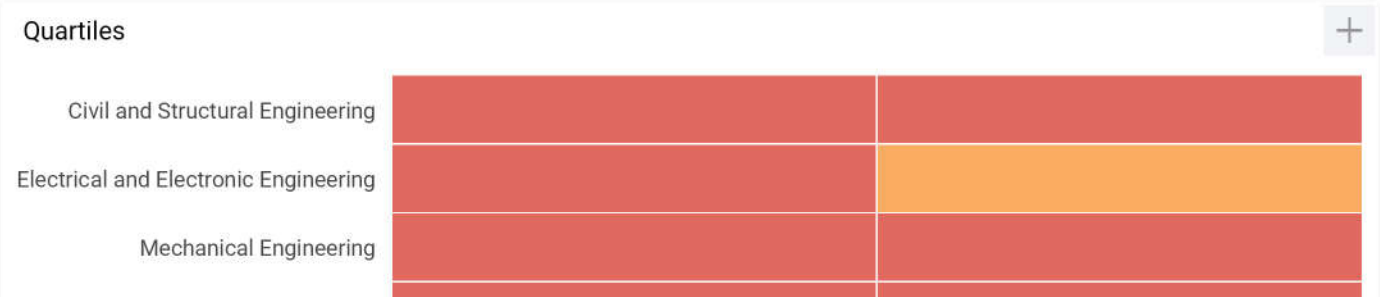
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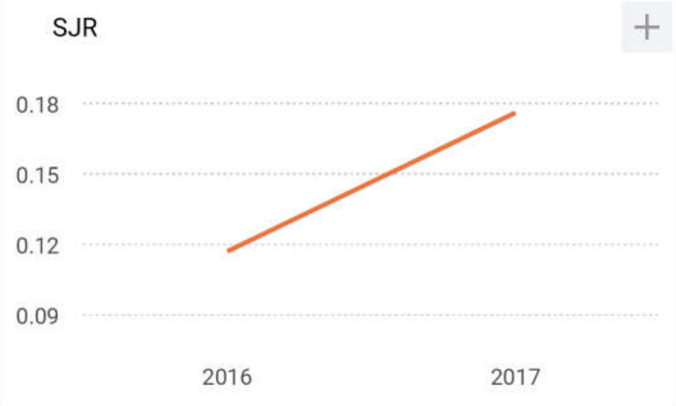
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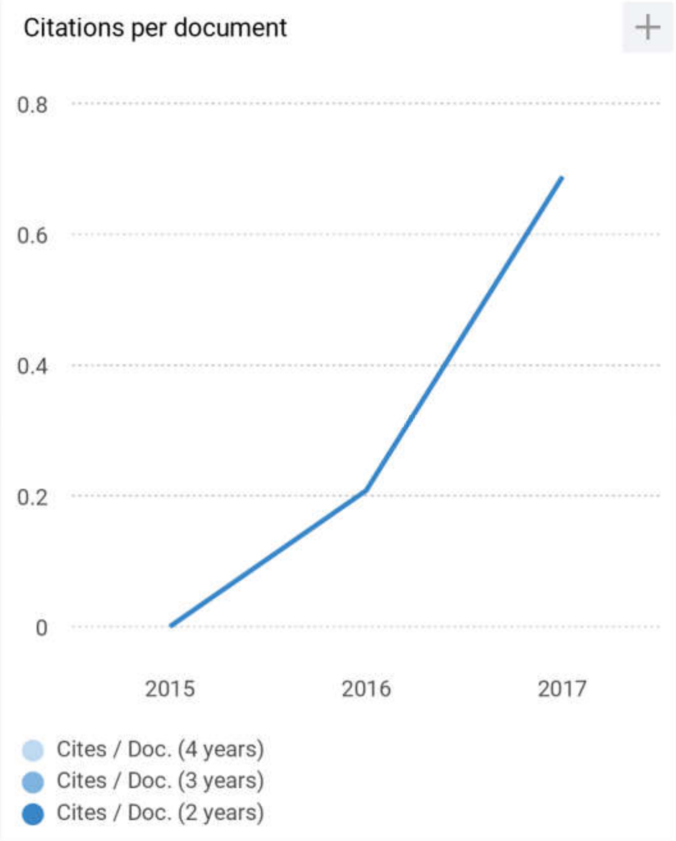
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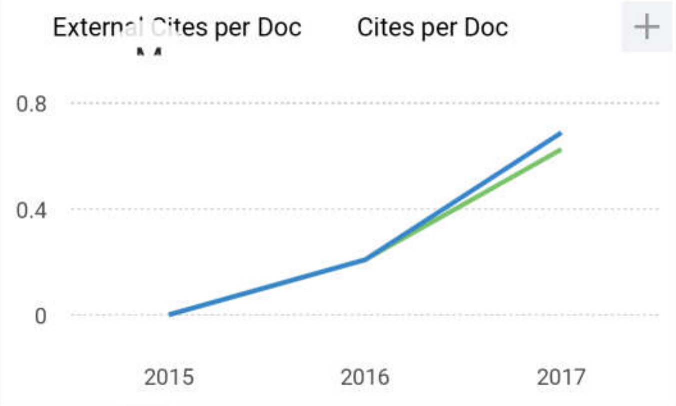
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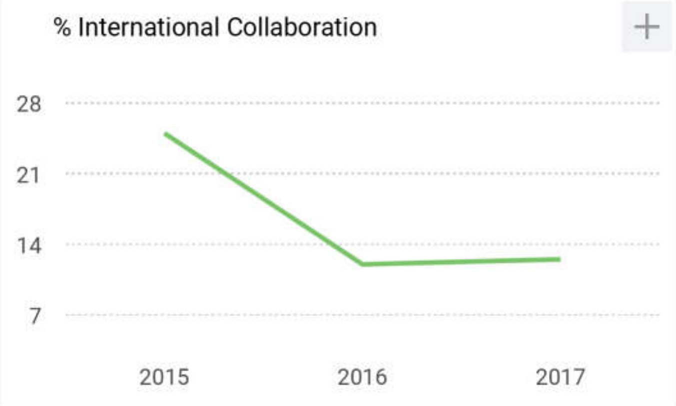
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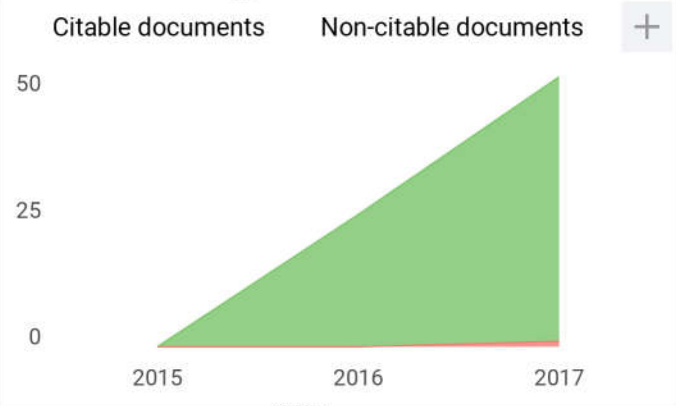
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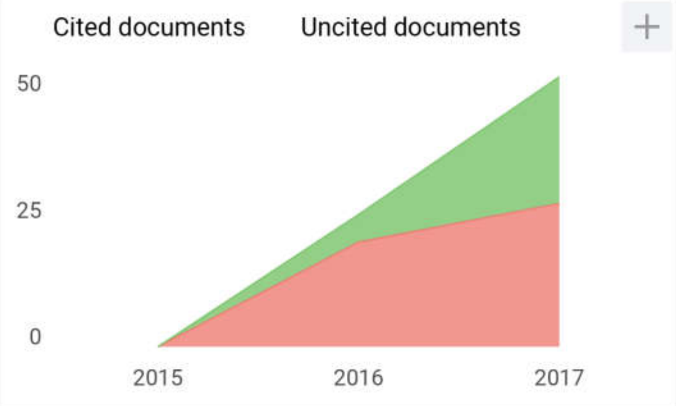
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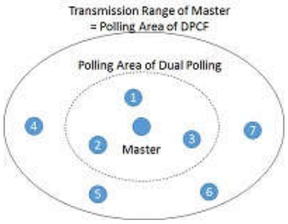

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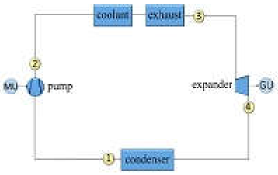

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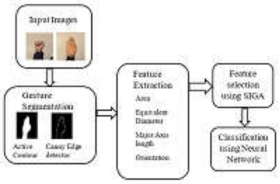

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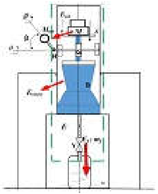

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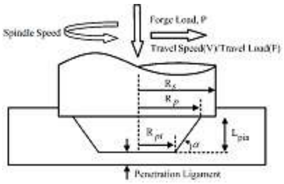

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Axial and Flexural Strength of Square RC Columns with No-rounded Corners Wrapped with CFRP under Eccentric Loading

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Abstract

This paper presents the results of a study on the axial and flexural strength of reinforced concrete (RC) columns with no-rounded corners wrapped with Carbon Fiber Reinforced Polymer (CFRP) under eccentric loading based on an experimental program. The main parameters under investigation are the number of layers of CFRP wrap. Thirty-six concrete cylinders with a standard size of (150×300) mm were cast and tested in this study to get the modulus of elasticity and compressive strength of concrete. Of these 36 concrete cylinders were divided into four groups, unwrapped, wrapped with one layer of CFRP, wrapped with two layers of CFRP, and wrapped with three layers of CFRP. Twelve rectangular reinforced concrete columns were also cast and tested in this study. The column specimens had dimensions (75×75×750) mm with no-rounded corners of the column section. The column specimens were also divided into four groups, unwrapped, wrapped with one layer of CFRP, wrapped with two layers of CFRP, and wrapped with three layers of CFRP. The experiment results showed that the load-carrying capacity of the wrapped column increased with the number of CFRP layers. A comparison between the experimental and theoretical results was also presented.

Keywords: square reinforced concrete column, no-rounded corners, carbon fiber reinforced polymer (CFRP), number of layers, eccentrically load, load-carrying capacity of column.

1. Introduction

Generally, the strength of structural elements in the construction of a building depends on the quality of material and the control of the construction process. During the construction of a building, it can sometimes happen that the compressive strength of concrete beams or columns do not comply with the standard of the design proposed by the structural engineer. There are two choices to solve this problem. First, the beam or column needs to be repaired or strengthened. Second, the dimension of the beam or column needs to be re-designed or re-calculated to meet the standards of design. If the first choice is selected, then the beams or the columns need to be strengthened.

There are several methods to strengthen an existing column. One of the methods is by jacketing or wrapping the column using a material such as Fiber Reinforced Polymer (FRP). In building construction, FRP is preferred to be used for strengthening reinforced concrete element of structures due to the high tensile strength, high corrosion resistance, light, and easy to install. There are several types of FRP generally used in building construction: Glass Fiber Reinforced Polymer (GFRP), Aramid Fiber Reinforced Polymer (AFRP), and Carbon Fiber Reinforced Polymer (CFRP). Particularly the last type (CRFP) is a common material used for shear-strengthening reinforced concrete element of the structures [1].

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The use of FRP for strengthening reinforced concrete element of the structures has been investigated by many of the researchers [1-5]. Several investigations were on FRP-strengthening reinforced concrete columns. Some researchers investigated the behavior of FRP-strengthening reinforced concrete columns under concentric loads [6-10]. In practice, a combination between compression axial load and bending moment always exists in the columns. Therefore, some investigations were carried out to examine the behavior of FRP-strengthening reinforced concrete columns under eccentric loading [11-14]. However, these investigations focused on the columns under eccentric loading that had acircular section. In construction sites, a column may have a circular or rectangular section. Therefore, some investigations were also carried out to examine the rectangular columns [15-18].

In practice, the rectangular column or square column usually has no-rounded corners (see Fig. 1(a)), because it is easier to make the rectangular column that has no-rounded corner than the column with rounded corners (see Fig. 1(b)). So that is why the rectangular or square columns with rounded corners in the real building construction are very rare. Hadi and Widiarsa [17] and Santos et al. [18] investigated the square column wrapped with CFRP but had rounded corners. Maaddawy [16] investigated the square column wrapped with CFRP had no-rounded corners using full and partially wrapped, but only one layer wrapping of CFRP. Therefore, a study of the axial and flexural strength of the square reinforced concrete column with no-rounded corners wrapped with several layers of CFRP under eccentric loading need to be carried out to examine the strengths and behaviors.

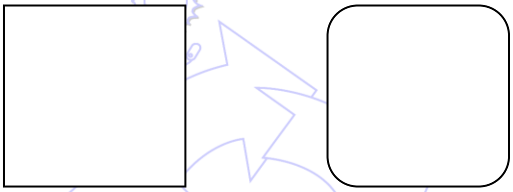
(a) No-rounded corner (b) Rounded corner

Fig. 1. No-rounded corners and rounded corner columns

The objective of this study is to examine the strength and behavior of the square RC column that has no-rounded corners and wrapped with CFRP under eccentric loading. The study is based on the experimental program. The result of the experimental program will be compared to some models which were proposed by some researchers, where one of the models is simply modified using no-rounded corners factor.

2. Experimental Program

2.1. Specimens preparation

The concrete of specimens was made in the Laboratory of Structures and Building Materials, Department of Civil Engineering, Universitas Atma Jaya Yogyakarta. The fine and coarse aggregates were used from local materials. The fine aggregates had the maximum size of 4.75 mm with fines modulus of 2.49, while the coarse aggregates had the maximum size of 20 mm with fines modulus of 7.88. The steel reinforcement bars with a diameter of 10 mm and 8 mm were used for reinforcing the column specimens. For wrapping the cylinder and column specimens, the CFRP was used in the form of rolls, 100 m in length and 500 mm in width. The fiber had a nominal thickness of 0.131 mm.

The parameter considered in this study was the number of CFRP layers. So, thirty-six concrete cylinders with a standard size of (150×300) mm were cast and tested in this study to get the modulus of elasticity and compressive strength of concrete. Of these 36 concrete cylinders were divided into four groups, unwrapped (SF0), wrapped with one layer of CFRP (SF1), wrapped with two layers of CFRP (SF2), and wrapped with three layers of CFRP (SF3) as shown in Table 1. The compressive strength of concrete was tested at 7, 14, and 28 days, while the modulus elasticity of concrete was tested only at 28 days.

Table 1 Cylinder specimen variation in the number of CFRP layer

Cylinder designation	Number of CFRP layer	Number of cylinder for compressive testing at 7, 14, and 28 days			Total of cylinders
		7 days	14 days	28 days	
SF0	-	3 cylinders	3 cylinders	3 cylinders	9
SF1	1	3 cylinders	3 cylinders	3 cylinders	9
SF2	2	3 cylinders	3 cylinders	3 cylinders	9
SF3	3	3 cylinders	3 cylinders	3 cylinders	9

Twelve column specimens having the section of (75×75) mm and the length of 750 mm were cast and tested in this study to get the behavior and the strength of the column specimens. Determination of short column classification was obtained using the Indonesian Building Code Requirements for Structural Concrete or SNI 2847-2013 [19]. Taking the effective length factor k = 1 and assumed for the nonsway frame column, it will give the value of slenderness ratio equal to 33.64. So this column is categorized as a short column. The twelve column specimens were divided into four groups, unwrapped (KF0), wrapped with one layer of CFRP (KF1), wrapped with two layers of CFRP (KF2), and wrapped with three layers of CFRP (KF3) as shown in Table 2.

Table 2 Column specimen variation in the number of CFRP layer

Specimen designation	Number of CFRP layer	Number of column specimen
KF0	-	3
KF1	1	3
KF2	2	3
KF3	3	3

The column section was (75×75) mm and had no rounded corner. The dimension of column specimen was designed to adjust along with the capacity of an actuator in the laboratory. The column specimen had four bars with a diameter of 10 mm as longitudinal bars and a diameter of 8 mm as a closed stirrup. The stirrup spacing was kept constant of 50 mm. The concrete cover was 20 mm on each side of column section. The detail reinforcement of a column section can be seen in Fig. 2. At both ends of the column, the specimen had ended corbels with an extra reinforcement to avoid premature failure at both ends and to be a location of the eccentric loading (see Fig. 3).

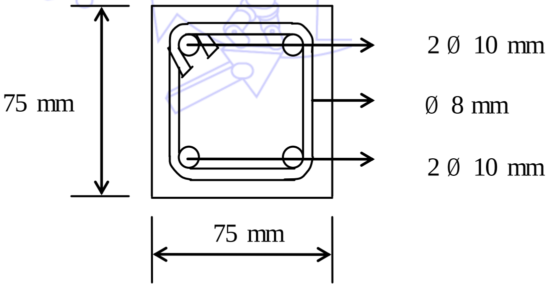

Fig. 2 Detail reinforcement of column section

Fig. 3 Detail of reinforcement column specimen

2.2. *Material testing*

Materials properties were obtained using the corresponding American Standards for Testing Materials (ASTM)[20]. The yield stress of reinforcement bars was obtained according to the guidelines in ASTM E8/E8M-09, Standard Test Methods for Tension Testing of Metallic Materials. The Universal Testing Machine (UTM) with a capacity of 30,000 kgf was used to conduct the tensile test of reinforcement bars. The average yield stresses of 240 MPa were obtained for both reinforcing bars of 10 mm and 8 mm. The testing of CFRP was not carried out in this study because the properties were already provided by the manufacturer. The properties of a dry CFRP provided by the manufacturer were (values in the longitudinal direction of fiber): tensile modulus of 234,000 MPa; tensile strength of 4,800 MPa; and elongation at break of 1.8 %.

2.3. *Cylinder and column specimens testing*

Thirty-six concrete cylinders were tested to obtain the modulus elasticity and compressive strength of concrete. The modulus of elasticity and compressive strength of concrete was performed according to ASTM C469/C469M-10 and C 39/C39M-10, respectively. Universal Testing Machine (UTM) with a capacity of 30,000 kgf was also used to test the modulus of elasticity and compressive strength of concrete as shown in Figs. 4 and 5, respectively.

Fig. 4 Modulus elasticity testing of cylinder concrete

Fig. 5 Compressive strength testing of cylinder concrete

Twelve column specimens were tested in the loading frame. An actuator with a load capacity of 250 kN was used to test all specimens. The specimen was tested in a horizontal position where the actuator was placed in one end of the specimen (see Fig. 6 and 7). The self-weight of the column in the transverse direction was ignored in the analysis. A loading head was placed in the actuator. The loading head consisted of two parts: a 20 mm thick steel plate and a reinforcement bar with a diameter of 19 mm as a ball joint. A steel corbel was placed at the other end of the specimen as a support to the spot where the same steel plate and ball joint were also placed in the support, so that both column supports can be assumed as pinned end supports. The load had eccentricity 50 mm from the longitudinal axis of the column specimen (see Fig. 8). The specimen was tested under load control. A Linear Variable Differential Transformers (LVDT) was used to measure deflection of the specimen. The LVDT was placed at the middle of the specimen to measure the displacement in the vertical direction. Measured data of the load and deflection were reading through a computer driven data acquisition system using a data logger.

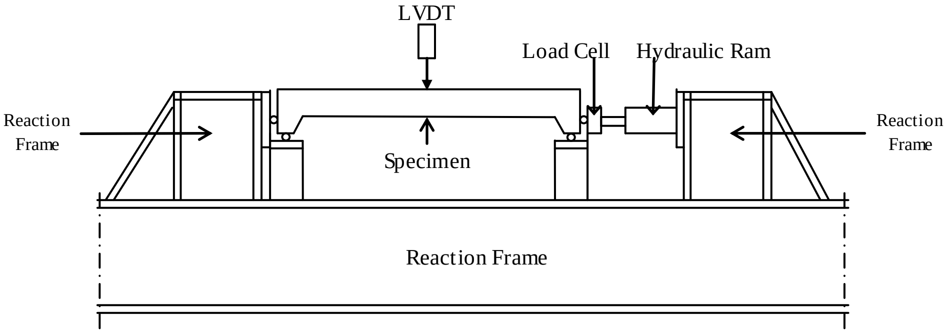

Fig. 6 Position of column testing

Fig. 7 Test setup

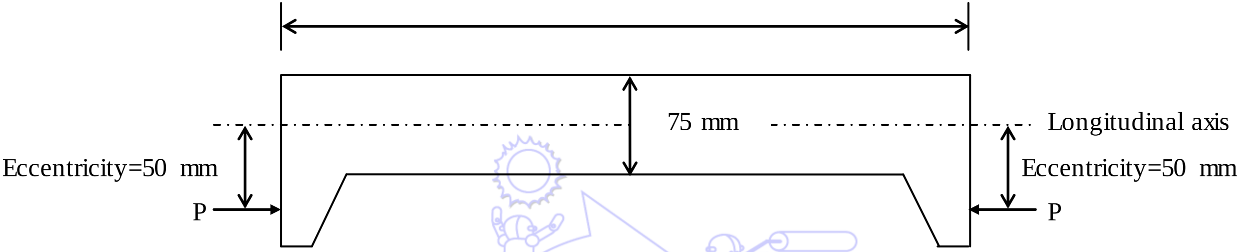

Fig. 8 The eccentricity load of column specimen

3. Experimental Results and Discussions

3.1. *Modulus of elasticity and compressive strength of concrete*

The modulus elasticity of concrete tested at 28 days was shown in Table 3. Table 3 showed that compare to the unwrapped specimen, the modulus elasticity of cylinder specimens wrapped with one layer, two, and three layers increased 10.19%, 15.65%, and 37.71%, respectively.

Table 3 Modulus elasticity of concrete at 28 days

Cylinder designation	Number of CFRP layer	The averaged modulus elasticity (MPa)	The increment compare to SC0 (%)
SC0	-	21,701.08	-
SC1	1	23,914.38	10.19
SC2	2	25,096.70	15.65
SC3	3	29,885.56	37.71

Table 4 Compressive strength of cylinder concrete and the increment compare to unwrapped cylinder specimen

Days	Cylinder designation	Number of CFRP layer	The averaged compressive strength (MPa)	The increment compare to unwrapped cylinder specimen (%)
7 Days	SA0	-	18.98	-
	SA1	1	33.29	75.40
	SA2	2	46.95	147.40
	SA3	3	54.45	186.90
14 Days	SB0	-	24.97	-
	SB1	1	37.25	49.20
	SB2	2	46.89	87.80
	SB3	3	62.03	148.40
28 Days	SC0	-	31.92	-
	SC1	1	35.07	9.90
	SC2	2	58.07	81.90
	SC3	3	65.22	104.30

The compressive strength of cylinder concrete tested at 28 days was summarized in Table 4. Compared to the unwrapped specimen, the cylinder specimens wrapped with one, two, and three layers tested at 7, 14, and 28 days showed the increase of compressive strength. At 28 days, the increment of compressive strength of the specimens wrapped with one layer, two layers, and three layers was compared to the unwrapped specimen at 9.9 %, 81.9 %, and 104.3 %, respectively.

3.2. *Behavior of column*

The load and the middle lateral displacement of column specimens were recorded during the testing. The load-lateral displacement relationship curve of one specimen representative of each group (unwrapped, wrapped with one layer, wrapped with two layers, and wrapped with three layers) can be seen in Fig. 9. Fig. 9 showed that the unwrapped column (KF0) was having the lowest strength compare to the wrapped columns (KF1, KF2, and KF3). Among the wrapped columns, the column wrapped with three layers had the highest strength. It was also observed that generally, the wrapped columns were more ductile than the unwrapped column. It can be seen from Fig. 9 that the curve strength of the unwrapped column after reaching the maximum load, will decrease rapidly. While the wrapped column, after reaching the maximum load the curve strength did not decrease rapidly and concluded by the long deformation before the collapse. It can be said that the CFRP wrapping increased the performance of the wrapped column. The CFRP wrapping compressed the concrete, so it would postpone the failure of the concrete as well as the failure of reinforcements.

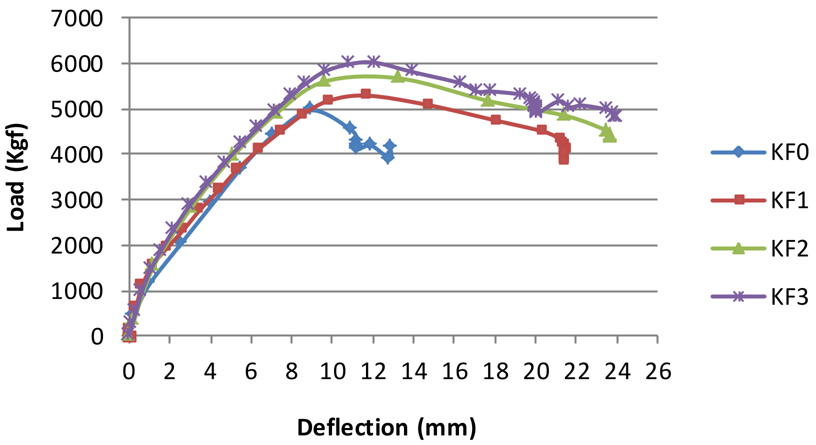

Fig. 9 Load-lateral displacement relationship of the specimens

3.3. *Column strength*

The maximum load-carrying capacity of the column specimens was recorded during the testing. The average maximum load-carrying capacity of the column was shown in Table 5. It can be seen from Table 5 that compared to the unwrapped column the differences averaged maximum load-carrying capacity of column wrapped with one layer, wrapped with two layers, and wrapped with three layers were 5.40 %, 10.71 %, and 16.30 %, respectively. These increments of the load-carrying capacity of the wrapped columns were due to the confinement of CFRP into the compressed concrete column. So, if the compressive strength of concrete increased due to the confinement of CFRP, the load-carrying capacity of the wrapped column also increased. Therefore, it can be said that the number of CFRP wrapping had a significant effect on the load-carrying capacity of the eccentrically loaded wrapped column.

Table 5 Averaged maximum load-carrying of the column specimens

Specimen designation	Number of CFRP layer	Averaged maximum load (Kgf)	The increment compare to KF0 (%)
KF0	-	4,932.98	-
KF1	1	5,199.50	5.40
KF2	2	5,461.29	10.71
KF3	3	5,737.25	16.30

3.4. Crack pattern

The first crack of the unwrapped column occurred in the tension fiber in the middle of the column (see Fig. 10). The first crack occurred when the tensile stress on the tension fiber is larger than the tensile strength of concrete. After the first crack, the crack, then propagated in the transverse direction of the column together with increasing the load. After reaching the maximum load, the compression fiber of concrete was crushing. It means that the strain of compression concrete increased and reached the maximum strain. After crushing of the compression concrete, the load decreased rapidly and the specimen was collapse.

Fig. 10 The crack pattern of the unwrapped column

Fig. 11 The crack pattern of the wrapped column

The crack pattern of the columns wrapped with one layer was the same as the column wrapped with two and three layers. The crack of the wrapped column occurred in the tension fiber at the end corbels where the location crack was in the zone out of the CFRP layers (see Fig. 11).This phenomenon crack that occurred in the zone out of the of CFRP layers indicated that the concrete in the zone of CFRP layers was confined very well. The crack at the end corbels occurred after the specimen reaching the maximum load-carrying capacity. The crack then propagated in the transverse direction of the column until the specimen collapsed. Before the specimen was collapse, the load decreasing slowly with long deformation. It indicated that the wrapped column was ductile specimen.

4. Comparison Model with the Experimental Results

4.1. Compressive strength

Richart, Brandtzaeg, and Brown [21] proposed a formula for predicting the compressive strength of FRP-confined circular concrete column:

$$\frac{f'_{cc}}{f'_c} = 1 + k_1 \frac{f_l}{f'_c} \tag{1}$$

where f'_{cc} = the compressive strength of the confined concrete; f'_c = the compressive strength of unconfined concrete; f_l = lateral confining pressure; and k_1 = the confinement effectiveness coefficient.

Teng, Chen, Smith, and Lam [22] modified Eq. (1) to predict the confined concrete strength of a rectangular column with inserting the shape factor (k_s) to consider the effect of no uniformity of confinement as follows:

$$\frac{f'_{cc}}{f'_c} = 1 + k_1 k_S \frac{f_l}{f'_c} \tag{2}$$

$$k_s = \left(\frac{b}{h}\right)\frac{A_e}{A_c} \tag{3}$$

$$\frac{A_e}{A_c} = \frac{1 - [(\frac{b}{h})(h - 2R_c)^2 + (\frac{h}{b})(b - 2R_c)^2]/(3A_g) - \rho_{sc})}{(1 - \rho_{sc})} \tag{4}$$

$$A_g = bh - (4-\pi)R_c^2 \tag{5}$$

$$f_1 = \frac{2 f_{frp} t_{frp}}{\sqrt{h^2 + b^2}} \tag{6}$$

$$f_{frp} = E_{frp}\varepsilon_{frp} \tag{7}$$

where b and h = width and height of column section, respectively; A_e = effective confinement area; A_c = total area of concrete; R_c = corner radius; and ρ_{sc} = cross-sectional area ratio of longitudinal steel.

In the column section with non-rounded corners, it was simply to substitute $R_c = 0$ into Eqs. (4) and (5). Hence, Eqs. (4) and (5) can be rewritten to become Eqs. (8) and (9), respectively:

$$\frac{A_e}{A_c} = \frac{1-[2bh]/(3A_g)-\rho_{sc}}{1-\rho_{sc}} \tag{8}$$

$$A_g = bh \tag{9}$$

While Lam and Teng [23] also proposed a formula to predict the confined concrete strength as follows:

$$\frac{f_{cc}^{'}}{f_c^{'}} = 1 + 3,3\ (\frac{A_e}{A_c})(\frac{f_l}{f_c^{'}}) \tag{10}$$

The compressive strength of the CFRP-wrapped concrete predicted by those models [21-23], where the model proposed by [22-23] was already modified by considering $R_c = 0$ (no-rounded corners) and the comparison to the experimental results were presented in Table 6. It can be seen from Table 6 that the differences of the compressive strength predicted by the model proposed by [21] with the experimental results for the specimens with one, two, and three CFRP layers were 16.7 %, -13.9 %, and -9.5 %, respectively. The differences in the model proposed by [22] with the experimental results for the specimens with one, two, and three CFRP layers were 8.2 %, -24.3 %, and -23.3 %.While the differences in the model proposed by [23] with the experimental results for the specimens with one, two, and three CFRP layers were 10 %, -22.1 %, and -20.4 %, respectively. Table 6 shows that the compressive strength of concrete wrapped with one CFRP layer predicted by the theories proposed by [21-23] were higher than the experimental results. However, predicting the compressive strength of wrapped concrete with two and three CFRP layers proposed by the same theories were lower than experimental results (in explanation of comparison was indicated by minus).

Table 6 Comparison of compressive strength of wrapped concrete

Number of CFRP layer	Compressive Strength, f'_{cc} (MPa)				Comparison		
	Model of Richart, Brandtzaeg, and Brown [21]	Model of Teng, Chen, Smith, and Lam [22]	Model of Lam and Teng [23]	Experimental	Model of Richart, Brandtzaeg, and Brown [21] to the Experimental	Model of Teng, Chen, Smith, and Lam [22] to the Experimental	Model of Lam and Teng [23] to the Experimental
1	40,95	37,95	38,59	35.07	1.167	1.082	1.100
2	49,99	43,98	45,27	58.07	0.861	0.757	0.779
3	59,02	50,00	51,94	65.22	0.905	0.767	0.796

4.2. *Load-carrying capacity*

The maximum load-carrying capacity and bending moment capacity of the eccentrically loaded column can be determined by using the following equations:

$$N_{max} = 0.85 f_c^{'} ab + A_s^{'} f_s^{'} - A_s f_s \tag{11}$$

$$M_{max} = N_{max}(e+\delta) \tag{12}$$

where N_{max} and M_{max} = the maximum load-carrying capacity and bending moment of columns, respectively; b = width of a column section; a = the depth of the equivalent rectangular concrete block; f_c' = the compressive strength of unconfined concrete; f_s Andf_s' = the stress of tension and compression steel, respectively; e and δ = the eccentricity of the load and the lateral deflection of the column, respectively.

The maximum load-carrying capacity of the wrapped column was calculated using Eq. (11) by replacing f_c' with f_{cc}' as formulated in Eqs. (1), (2), and (10) as proposed by [21-23], respectively. The maximum load-carrying capacity of the wrapped column predicted by the equation proposed by [21-23], where the model proposed by [22-23] were already modified by considering R_c = 0 (no-rounded corners) and the comparison to the experimental results were presented in Table 7.

Table 7 Comparison the maximum load-carrying capacity of the wrapped column

Number of CFRP layer	The maximum load-carrying capacity, N_{max} (kgf)				Comparison		
	Model of Richart, Brandtzaeg, and Brown [21]	Model of Teng, Chen, Smith, and Lam [22]	Model of Lam and Teng [23]	Experimental	Model of Richart, Brandtzaeg, and Brown [21] to the Experimental	Model of Teng, Chen, Smith, and Lam [22] to the Experimental	Model of Lam and Teng [23] to the Experimental
1	5356.15	5192.63	5226.77	5199.50	1.030	0.998	1.005
2	5788.85	5499.93	5552.90	5461.29	1.059	1.007	1.017
3	6188.98	5777.57	5869.42	5737.25	1.078	1.007	1.023

It can be seen from Table 7 that the differences the maximum load-carrying capacity predicted by the model proposed by [21] with the experimental results for the specimens with one, two, and three CFRP layers were 3 %, 5.9 %, and 7.8 %, respectively. The differences in the model proposed by [22] with the experimental results for the specimens with one, two, and three CFRP layers were -0.1 %, 0.7 %, and 0.7 %. While the differences in the model proposed by [23] with the experimental results for the specimens with one, two, and three CFRP layers were 0.5 %, 1.7 %, and 2.3 %, respectively. It can be said that the load-carrying capacity of the wrapped column proposed by [22] which was already modified by considering R_c = 0 (no-rounded corners) was close to the experimental results.

The maximum bending moment of the wrapped column calculated using Eqs. (11) and (12) replacing f_c' with f_{cc}' as formulated in Eqs. (1), (2), and (10) as proposed by [21-23], respectively. The maximum bending moment of the wrapped column proposed by [21-23] and compared with experimental results were presented in Table 8.

Table 8 Comparison the maximum bending moment of the wrapped column

Number of CFRP layer	The maximum bending moment, M_{max} (kgf-mm)				Comparison		
	Model of Richart, Brandtzaeg, and Brown [21]	Model of Teng, Chen, Smith, and Lam[22]	Model of Lam and Teng[23]	Experimental	Model of Richart, Brandtzaeg, and Brown [21] to the Experimental	Model of Teng, Chen, Smith, and Lam[22] to the Experimental	Model of Lam and Teng[23] to the Experimental
1	324,957.62	315,036.86	317,108.14	315,453.67	1.030	0.998	1.005
2	356,419.50	338,630.69	341,892.05	336,251.63	1.059	1.007	1.017
3	384,335.66	358,787.10	364,490.98	356,283.23	1.078	1.007	1.023

It can be seen from Table 8, that the differences in the maximum bending moment predicted by the model proposed by [21] with the experimental results for the specimens with one, two, and three CFRP layers were 3 %, 5.9 %, and 7.8 %, respectively. The differences in the model proposed by [22] with the experimental results for the specimens with one, two, and three CFRP layers were -0.1 %, 0.7 %, and 0.7 %. While the differences in the model proposed by [23] with the experimental results for the specimens with one, two, and three CFRP layers were 0.5 %, 1.7 %, and 2.3 %, respectively. From this comparison of the maximum bending moment, it can be said that the load-carrying capacity of the wrapped column proposed by [22] which was already modified by considering $R_c = 0$ (no-rounded corners) was close to the experimental results.

The predicting of load-carrying capacity and maximum bending moment by the models gives slightly different compare to experiment result. The differential value of load-carrying capacity and maximum bending moment between the models and experiment program is probably due to the boundary condition of the models and experimental program. As mentioned above that in this experimental program, the both column supports were using steel plate and ball joint. These supports were assumed as pinned supports. This boundary condition might be as idealistic as the model. However, it can be seen from the comparison above that the prediction of load-carrying capacity and maximum bending moment using an equation that was proposed by [22] and which was already modified by considering $R_c = 0$ (no-rounded corners) was close to the experimental results.

5. Conclusions

Based on the experimental program and comparison with several models proposed by several researchers, the following conclusions can be drawn:

(1) The number of CFRP wrapping significantly increased the load-carrying capacity of the eccentrically loaded column that has no-rounded corners. The confining of CFRP made the failure of concrete and reinforcement was postponed. Therefore, the ductility of wrapped column was also increased.

(2) Predicting the compressive strength for one CFRP layer using the model proposed by [21-23] gave higher strength compared to the experimental result. However, predicting the compressive strengths for two and three CFRP layers using the model proposed by [21-23] were lower than experimental results.

(3) The maximum load-carrying capacity and bending moment predicted using the model proposed by [21-23], and compared to the experimental results gave that model proposed by [22] which was already modified by considering $R_c =$ 0 (no-rounded corners) was close to the experimental result.

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