

FRP-CONFINED CIRCULAR COLUMNS UNDER SMALL ECCENTRIC LOADING

BY

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ABSTRACT

Fiber reinforced polymers (FRP) confined concrete columns benefit from a confining effect due to restraint of the lateral expansion. More research work is necessary in order to investigate the behavior of RC columns confined by FRP under small eccentric loads. Eighteen FRP-confined concrete circular columns were tested under small eccentric compression loading until failure. These specimens were strengthened by a full confinement. The small load eccentricity and slenderness ratio were the basic parameters considered in the experimental program. The effect of small load eccentricity on the ultimate load and ductility of confined columns with different slenderness ratio were reported. A significant decrease in confinement effect was found with the increase of load eccentricity. An empirical equations based on regression analysis of experimental results were proposed, that can be used to determine the ultimate load of FRP-confined concrete columns taking into account small load eccentricity as well as slenderness ratio of columns. The present study can be considered as an attempt to define the real behavior of CFRP-confined compression members, as the available data on axially loaded confined members can not give accurate information on behavior of confined compression members.

Keywords: column, confinement, FRP, eccentric load, ultimate load

1. INTRODUCTION

Lateral confinement of concrete columns by means of FRP-wrapping will increase compressive strength and ultimate strain (ductility). Most investigations have been directed to axially loaded columns with zero eccentricity, such as ^{1,2,3,9,10,11} show that the strength and ductility increases for concrete columns confined with FRP shell. However, more research work is necessary in order to investigate the behavior of RC columns confined by FRP under eccentric loads ^{8,13}, as it seems that axially loaded columns do not exist in practice, therefore a minimum eccentricity recommended in most codes, and that is why small eccentrically loaded columns may be more representative ^{4,5,6,7}. Eighteen FRP-confined concrete circular columns were tested under small eccentric compression loading until failure. These specimens were strengthened by a full confinement. The small load eccentricity and slenderness ratio were the basic parameters considered in the experimental program. The effect of small load eccentricity on the ultimate load, axial and lateral strain and ductility of confined columns with different slenderness ratio were reported. It was found that the load carrying capacity of FRP-confined columns was very sensitive to small load eccentricity, where a significant decrease in confinement effect was found with the increase of load eccentricity. An empirical equations based on experimental results were proposed, that can be used to determine the ultimate load of FRP-confined concrete columns taking into account small load eccentricity as well as slenderness ratio of columns. This study can be considered as an attempt to define the real behavior of CFRP-confined compression members.

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2. EXPERIMENTAL PROCEDURE

A comprehensive testing program on axially as well as small eccentrically loaded columns confined with CFRP was carried out. The test program consists of three groups as shown in Table (1), these groups contain 18 RC columns. The specimens diameter was 150mms while its heights were varied. Four different column heights were taken in this study such as: 300mms, 610 mms, 915 mms and 1220 mms. The heights to diameter ratios (slenderness ratio), H/D were 2, 4, 6 and 8. The steel ratio of longitudinal reinforcement were constant for all columns and equal to 2.2% with yield stress 365MPa. The used concrete was made from a mix of ordinary Portland cement, natural sand, and gravel with the mixture proportion shown in Table (2). The average compressive strength of the concrete (unconfined concrete strength) was determined to be 20MPa based on the on the compressive test result of six standard cylinders (150x300mm). Nine specimens were confined with one layer of full horizontal wrapping of CFRP, while the other specimens were control (unconfined). The properties of CFRP wrapping are shown in Table (3). The tested specimens were loaded to failure under increasing compressive load, with variable load eccentricity. The Load eccentricity, e , was taken 0D, 0.05D and 0.1D, where D is the column diameter. The columns were tested under monotonically increasing axial compression with constant end eccentricity. Load was applied through steel end plates and adjustable rollers “pin support” that provide a constant end eccentricity. Three pin supports were manufactured specially for the present work.

Steel loading frame with hydraulic jack was used to apply vertical load on columns, while the prisms and cylinders were tested by Amsler, 3000kN compression testing machine. Fig. (1) shows test setup for axially loaded columns and Fig. (2) shows test setup for eccentrically loaded columns. The capacity of the hydraulic jack applying the vertical load was 1100kN. Load cell with capacity of 950kN and accuracy of 0.1kN was used. The value of applied load was appeared automatically on special monitor connected to the load cell.

Columns were tested using an incremental loading procedure. Approximately twenty load increments were required for unconfined columns while thirty load increments were required for confined columns. Each load increment was applied in period of about two minute. The load was kept constant at each load stage for about ten minutes to allow measurements and observations.

The lateral strains in the specimens were measured by using two 60 mm surface gauges placed at 180^0 apart attached at the midheight of each specimens. Another two 30 mm surface gauges were attached at the surface of CFRP. Moreover, to measure axial strains, linear variable displacement transducers (LVDT_s) were placed at 180^0 apart around the specimens. The LVDT_s used have a maximum range of (50mms) and capable of recording (0.01mms) displacement. The results from LVDT_s were compared with those of the electrical gauges. It was observed that for all practical purposes, the average axial strains measured by LVDT_s were as accurate as the measurements made with the electrical strain gauges. Lateral deflection of eccentrically loaded columns was measured at mid height of the columns using LVDT_s.

Table (1) Overview of the tested columns

Groups	Specimen No.	D, mms	H, mms	Steel Ratio, μ %	e/D
G1	G 1,1u	150	1220	2.22	0
	G 1,1c	150	1220	2.22	0
	G 1,2u	150	1220	2.22	0.05
	G 1,2c	150	1220	2.22	0.05
	G 1,3u	150	1220	2.22	0.1

	G 1,3c	150	1220	2.22	0.1
G 2	G 2,1u	150	915	2.22	0
	G 2,1c	150	915	2.22	0
	G 2,2u	150	915	2.22	0.05
	G 2,2c	150	915	2.22	0.05
	G 2,3u	150	915	2.22	0.1
	G 2,3c	150	915	2.22	0.1
G 3	G 3,1u	150	610	2.22	0
	G 3,1c	150	610	2.22	0
	G 3,2u	150	610	2.22	0.05
	G 3,2c	150	610	2.22	0.05
	G 3,3u	150	610	2.22	0.1
	G 3,3c	150	610	2.22	0.1

D= Column diameter, H= Column height, e= Load eccentricity, u= Unconfined columns, c= Confined columns

Table (2); Mixture proportion of concrete (percentage by weight)

Sand	Gravel	Cement	Water
28.7	48.8	15.2	7.3

Table (3) Mechanical Properties of CFRP

Fiber type	High strength carbon fibers
Fiber orientation	0° unidirectional
Young's modulus	233.333GPa
Fabric design thickness	0.16mm
Tensile strength	3500MPa
Elongation at break	1.5%

Fig. 1 Test setup for axial loading

Fig. 2 Test setup for eccentric loading

3. TEST RESULTS AND DISCUSSIONS

3-1 Test Observations and Modes of Failure

For Axially loaded columns the failure of unconfined columns was generally marked by the appearance of vertical cracks at about 90% of the ultimate load followed by crushing of concrete at or near the midheight of the specimen. There was no indication of any reinforcement buckling until the concrete was completely crushed. No overall buckling as result of slenderness was noticeable, as the length effect were insignificant within the range of (H/D) ratios studied. Failure of confined specimens was generally marked by sudden fracture of the CFRP wrapping at or near the midheight of the specimen. Failure near the top and bottom edges was not detected. Sounds heard during the early to middle stages of loading were attributed to the microcracking of concrete and shifting of aggregates. Snapping of the CFRP layers could be heard near the end of the loading process.

For eccentrically loaded columns the failure of unconfined columns was generally marked by crushing of concrete at compression side at or near the midheight of the specimen. There was no indication of any reinforcement buckling until the concrete was completely crushed. The observed behavior of the confined columns was similar to the unconfined columns up to the peak load of unconfined columns. Increases in the lateral deflection of confined columns resulted in the concrete failing in compression and rupturing the FRP confining jacket at approximately mid-height. Tensile rupture of the composite was only caused by a significant increase in the lateral deflection beyond the peak load. The deflected shape of the columns at peak load was symmetrical and there was no local buckling in the columns. The only signs of distress to the composite were the heard sounds and the large lateral deflections of the columns. Inspection of the concrete core after failure showed the concrete to be of a highly fissured nature, but re-compacted under the high triaxial state of stress. The modes of failure of some unconfined and confined columns with eccentricity $e/D=0.05$ are shown in Figs. 3 and 4.

3-2 Axial strain

The ultimate load and axial strain of all columns are presented in Table (4) and Fig. (5). For unconfined columns the load-vertical strain relationship was approximately second-degree curve with ultimate strain of about 0.0025. The behavior of the confined columns was similar to the unconfined columns up to the peak load. A review of response curves indicates a significant enhancement in strength and ductility of concrete confined with CFRP. Furthermore, unlike steel-encased concrete, response of CFRP-confined concrete was bilinear with no descending branch. The response consists of three regions. In the first region, behavior was similar to unconfined column, since lateral expansion of the core was insignificant. With the increase in microcracks, a transition zone was entered where the CFRP jacket exerts a lateral pressure on the core to counteract the stiffness degradation of concrete. Finally, a third region was recognized in which the CFRP jacket was fully activated, and the stiffness was generally stabilized around a constant rate. The response in this region was mainly dependent on the stiffness of the CFRP jacket.

Table (4): Summary of test results

Groups	Spec. No.	Cracking Load P_{cr} kN	Ultimate Load P_u kN	Ultimate Vertical Strain		Ultimate Lateral Strain		Ultimate Lateral deflection, mm
				$\epsilon_{Min.}$	$\epsilon_{Max.}$	$\epsilon_{Min.}$	$\epsilon_{Max.}$	
G1	G 1,1u	415	462	0.002	0.002	0.0004	0.00039	0.0
	G 1,1c	----	772	0.028	0.028	0.0149	0.01480	0.0
	G 1,2u	386	420	0.0015	0.0024	0.0003	0.00042	0.40
	G 1,2c	---	700	0.0180	0.029	0.0144	0.0146	1.15
	G 1,3u	360	393	0.0012	0.0028	0.0002	0.00042	0.99
	G 1,3c	---	588	0.0110	0.030	0.0149	0.0148	2.85
G2	G 2,1u	395	442	0.0021	0.0021	0.0004	0.0004	0.0
	G 2,1c	---	720	0.0210	0.0200	0.0144	0.00146	0.0
	G 2,2u	365	402	0.0016	0.0026	0.0149	0.0146	0.65
	G 2,2c	---	640	0.012	0.030	0.0148	0.0148	2.00
	G 2,3u	345	381	0.001	0.0028	0.0002	0.0006	1.37
	G 2,3c	---	510	0.011	0.030	0.0145	0.0146	4.54
G3	G 3,1u	385	421	0.0022	0.0021	0.00041	0.00041	0.0
	G 3,1c	---	658	0.0175	0.0174	0.0149	0.150	0.0
	G 3,2u	355	391	0.0017	0.0028	0.0003	0.0005	1.11
	G 3,2c		565	0.0108	0.0180	0.0148	0.0148	3.20
	G 3,3u		359.2	0.0012	0.0030	0.00025	0.00063	2.30
	G 3,3c	---	420	0.0076	0.0190	0.0150	0.0150	6.80

3-3 Load-deflection curves

The load-deflection curves for cases of $e/D=0.05$ and 0.1 are shown in Figs. (6) and (7), respectively. As the axial load increases, larger lateral deflections are observed for columns with H/D equal to 6 and 8. It is noticed that, the columns with bigger values of e/D have bigger values of lateral deflection of the same H/D ratio. That is because, the compressive strain increases in one side of the column than that in the other side. This action lead to increase in curvature and consequently increase in lateral deflection. As mentioned before, the lateral deflection of confined columns was very big with respect to that of unconfined columns. That is because, the value of lateral deflection is mainly depend on the curvature, that in tern depends on the deference between the maximum and the minimum strains developed on either sides of the column. The differences between maximum and minimum strains for confined columns was about ten time of that for unconfined columns.

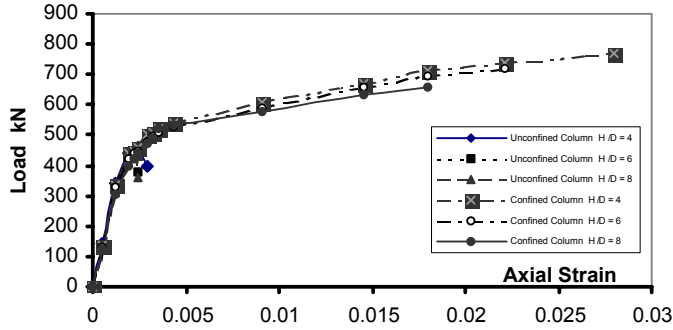


Fig. 5 Load-Axial strain curves for the tested columns

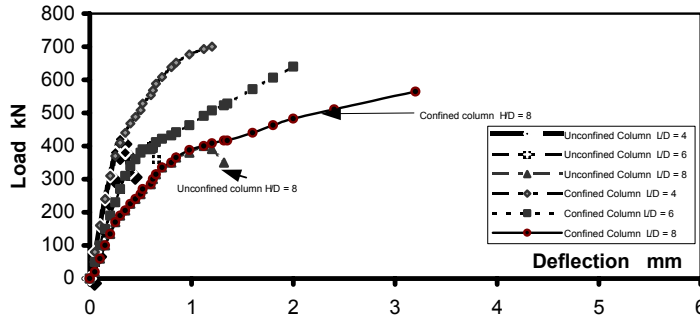


Fig. 6 Load deflection curves for the tested columns " e/D = 0.05 "

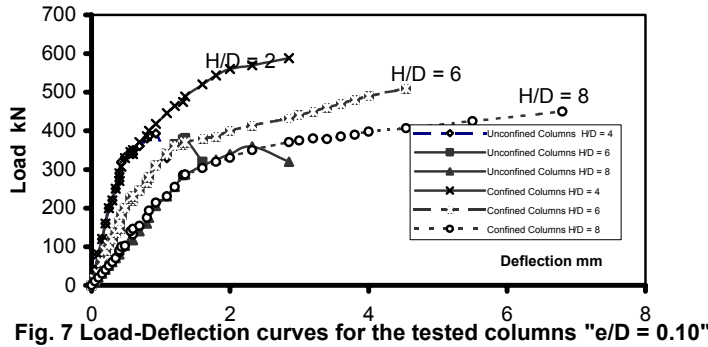


Fig. 7 Load-Deflection curves for the tested columns "e/D = 0.10"

3-4 Ultimate load

The effect of load eccentricity on ultimate load for different values of H/D for unconfined and confined columns is illustrated in Table (4) and Fig. (8). It is clear that, the effect of load eccentricity on ultimate load of confined columns is greater than that of the unconfined columns, and this effect is very sensitive to H/D ratios. The ultimate load of confined and unconfined columns (for H/D=4) reduced by about 36% and 14.7%, respectively, by increasing load eccentricity from 0.0D to 0.1D. The column load gain due to confinement is defined by the following equation:

$$Load\ gain = \frac{P_{u,confined} - P_{u,unconfined}}{P_{u,unconfined}} \times 100 \quad (1)$$

Table (4) shows the load gain for confined columns for different ratios of H/D and e/D. It is concluded that the procedure of confined columns couldn't use for unconfined columns, in case of small eccentricity. Therefore, a new accurate design equation take the small eccentricity as well as size effect is essential.

Table (4) Load gain of confined columns

Load Eccentricity, e	Load gain%			
	H/D	4	6	8
0.0D		67.1	62.8	56.3
0.05D		65.1	59.2	44.5
0.1D		49.6	33.8	16.9

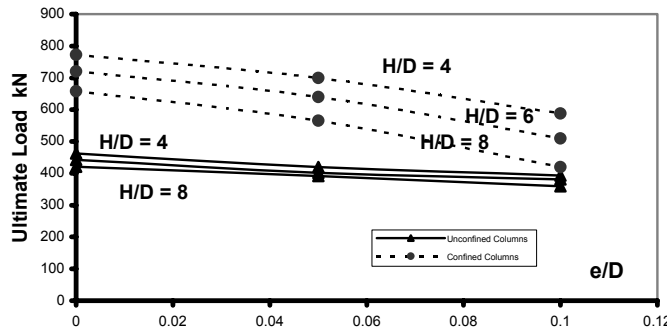


Fig. 8 Effect of load eccentricity on ultimate load of confined and unconfined columns

3-5 Effect of slenderness ratio on ultimate load

From experimental work it was observed that no overall buckling for studied H/D ratios. Table (3) and Fig. (8) show that the ultimate load decreases with the increase H/D and e/D ratios. It is clear that, the effect of slenderness ratio on ultimate load of confined columns is greater than that on unconfined columns, and this effect is very sensitive especially with the increase of e/D ratios. Thus the column will be subjected to a total moment given by Eqn. (2).

$$M_{total} = P(e_o + \delta) \quad (2)$$

where : P = applied load, e_o = initial eccentricity and δ = lateral deflection

$$\delta = R(1 - \cos \frac{\phi}{2})$$

$$R = H / \phi$$

ϕ = angle of curvature

$$= (\varepsilon_{c,max} - \varepsilon_{c,min}) \frac{H}{D} \text{ rad}$$

Then, $\delta = \frac{2H}{\phi} \sin^2(\phi/4)$, see Fig. 9.

3-6 Effect of slenderness ratio on ultimate confined stress and strain

Four different H/D ratios were taken in this study, such as:2, 4, 6 and 8. It was founded that the ultimate confined strength of the columns affected by the slenderness ratio as shown in Fig. (10). The ultimate stress and strain of confined columns with any slenderness ratios can be obtained by regression analysis of test results as related to that for concrete cylinder (i.e. H/D=2) in the following form of Eqns. (3) and (4):

$$f_{cu} = f_{cu,2:1} \left(0.0012 (H/D)^2 - 0.0535 (H/D) + 1.1 \right) \quad (3)$$

$$\varepsilon_{cu} = \varepsilon_{cu,2:1} \left(0.0063 \left(\frac{H}{D} \right)^2 - 0.1475 \left(\frac{H}{D} \right) + 1.275 \right) \quad (4)$$

Where: $f_{cu,2:1}$ = ultimate confined stress of concrete cylinder
 $\varepsilon_{cu,2:1}$ = ultimate confined strain of concrete cylinder

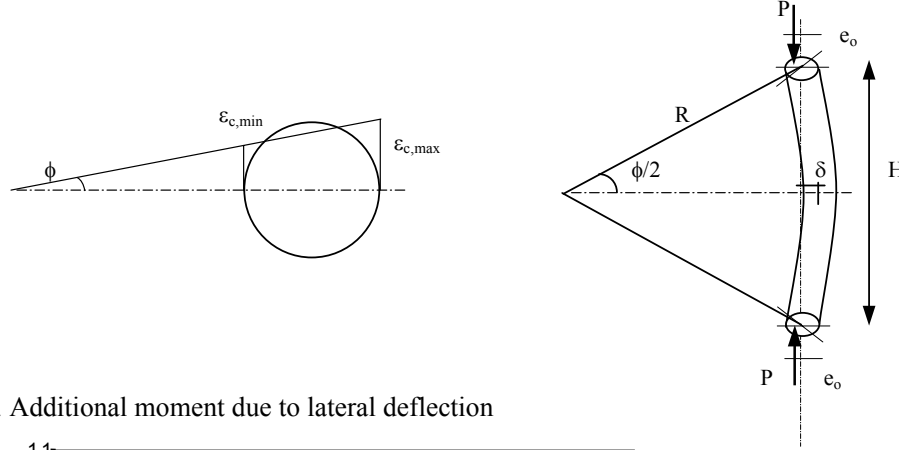


Fig. 9. Additional moment due to lateral deflection

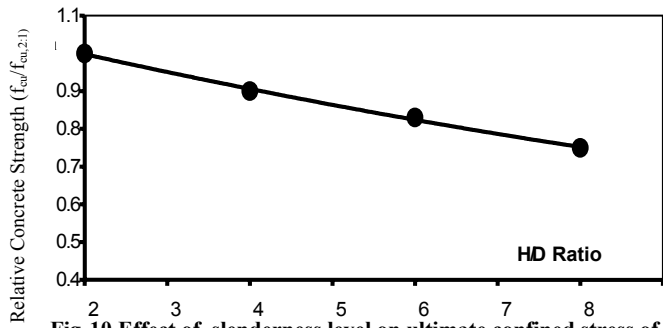


Fig 10 Effect of slenderness level on ultimate confined stress of CFRP confined concrete columns

4. PROPOSED EXPRESSION OF ULTIMATE LOAD OF FRP-CONFINED RC SHORT COLUMNS

The failure load of FRP-confined concrete columns with small eccentricity (according to E.C.O.P) can be obtained by regression analysis of test results taking the H/D ratio in account in the following form of Eqn. (5):

$$P_u = k_1 k_2 A_c f_{cu} + A_s f_y \quad (5)$$

Where :

P_u = failure load,

A_c = cross sectional area of concrete column,

A_s = cross sectional area of longitudinal reinforcement,

f_y = yield stress of steel,

f_{cu} = ultimate confined stress of concrete,

k_1 = strength reduction factor due to size effect,

k_2 = strength reduction factor due to small load eccentricity.

And,

$$k_1 = 0.00120 (H/D)^2 - 0.05350(H/D) + 1.1 \quad (6)$$

$$k_2 = -0.0052 (H/D)^2 + 0.0430 (H/D) + 0.811 \quad \text{“for } e/D = 0.05\text{”} \quad (7)$$

$$k_2 = -0.00560 (H/D)^2 + 0.0237 (H/D) + 0.710 \quad \text{“for } e/D = 0.10\text{”} \quad (8)$$

For purpose of design, the reduction factors ($k_1 \cdot k_2$) of concrete should not exceed $0.67f_{cu}/\gamma_c \approx 0.447$ and strength reduction factor of steel is 0.87 (according to E.C.O.P)
 Table (5) and Fig. (11) provides an iterative values of the strength reduction factors k_1 and k_2 as a function of e/D and H/D that can be easily applied to practical situation.

Table (5) Strength reduction factor for Load eccentricity and H/D Ratio

H/D	4	5	6	7	8	9
K₁	0.905	0.863	0.822	0.784	0.7488	0.716
K₂	e/D=0.05	0.899	0.896	0.880	0.857	0.822
	e/D=0.10	0.715	0.689	0.651	0.601	0.541

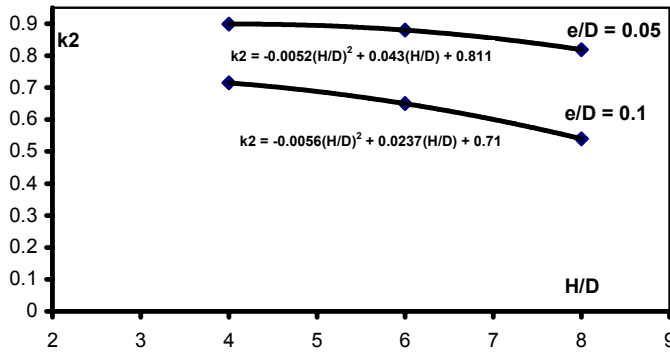


Fig. 11 Strength Reduction Factor (k2) Due to Load Eccentricity

To investigate the validation of the proposed formulation the circular column illustrated in Fig. (12) is investigated. Due to aggressive environment and creep rupture, Ref.[8] recommended to multiply the ultimate strength and strain of CFRP by a reduction factors equal to 0.85 and 0.55 respectively.

The ultimate tensile strength of CFRP= $0.85 \times 0.55 \times 3500 = 1636 \text{MPa}$.

The ultimate strain of CFRP= $0.85 \times 0.55 \times 0.015 = 0.007 \text{mm/mm} < 0.004$ Ref. [8].

The corresponding ultimate design strength of CFRP, $f_{ujd} = 0.004E_j = 0.004 \times 233333 = 933 \text{MPa}$.

From Table (5) $k_1 = 0.759$ and $k_2 = 0.833$. But $k_1 k_2 > 0.35$, then taken 0.35.

Using Eqn. (5) with reduction factors, it can be calculate the ultimate confined strength of concrete at required ultimate load 1800kN, as:

$1200000 = 0.35 \times 96211 f_{cu} + 0.87 \times 791.7 \times 360$, then $f_{cu} = 28.09 \text{MPa}$.

From Ref. [12], it can be calculate the ultimate lateral pressure of CFRP, f_{LU} , as:

$$f_{cu} = f_{co} + 5(f_{LU})^{0.8}$$

$28.09 = 25 + 5(f_{LU})^{0.8}$, then $f_{LU} = 0.811 \text{MPa}$.

The number of CFRP plies can obtained from the following equation:

$$f_{LU} = 0.5k_e \rho_j f_{ujd}, \text{ where } k_e = 1 \text{ for full wrapping.}$$

But $\rho_j = 4n t_j / D$, where, n = number of plies and t_j = CFRP thickness. $n = 1.5$, then use 2 continuous CFRP plies to increase the ultimate column load of about 30%.

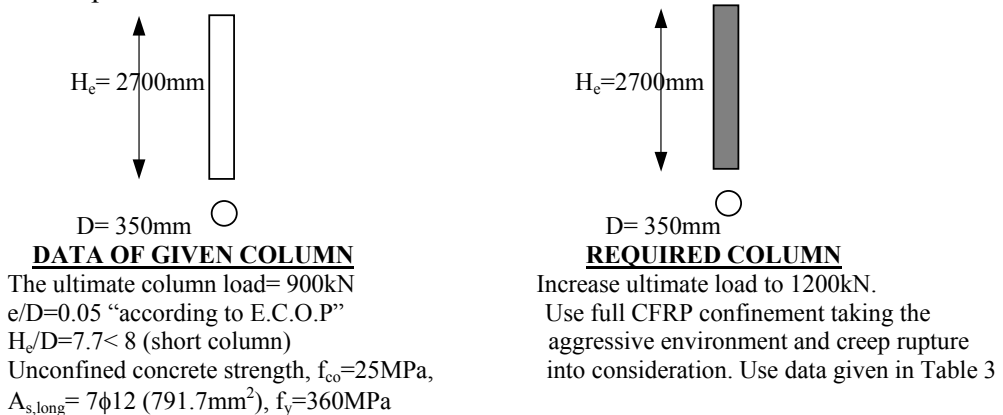


Fig. 12 Illustrated example

5. CONCLUSIONS

The present research has investigated the real behavior of axially FRP-confined concrete columns taking the effect of small eccentricity in accordance to most international codes, in contrary most researches that take the load eccentricity equal to zero. The result of experimental program has been reported in details. Findings from this study show that:

1. The use of fiber composites is an efficient means of providing confinement of concrete for strength and ductility enhancement.
2. Under relatively small load eccentricities, e/D from 0.05 to 0.10, the behavior of eccentrically loaded FRP-confined columns demonstrate a completely different behavior specially the load carrying capacity.
3. A proposed equations to calculate the ultimate confined stress and strain as a function if slenderness ratio are suggested.
4. The present paper proposed an equation to be calculate the failure load of reinforced concrete FRP-confined columns taking small eccentricity and slenderness ratio into account.

ACKNOWLEDGMENT

The work described in this paper was conducted by fifth author as a part of his Ph.D studies at the University of Tanta under the supervision of the other authors. The experimental work was performed in the Reinforced Concrete and Heavy Construction Laboratory of the Faculty of Engineering, Tanta University.

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