

compression

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ABSTRACT: The behaviour of fiber reinforced polymer (FRP)-confined concrete has been extensively studied. Most of the existing models have been concerned with small-size cylinders. This paper presents the experimental and analytical results of axially loaded large-scale columns confined with FRP wrapping reinforcement. The effective circumferential FRP failure strain and the effect of increasing confining action were investigated. The reliability of different models for the prediction of the ultimate strength of FRP-confined concrete has been verified when applied to real scale axially loaded columns. A revision of an existing model developed earlier by the first author was presented. The revised model addresses the effective FRP failure strain that is attributed to localized stress concentrations near failure due to non-homogenous deformations of the damaged concrete. A comparison between the experimental results and those predicted by the existing models was investigated. Based on the model verification, results show that only few of these models seem to predict the behaviour of the tested large-scale columns accurately.

1 INTRODUCTION

Concrete columns have an important function in the structural concept of many structures. Often, these columns are vulnerable to exceptional loads (such as impact, explosion or seismic loads), load increase (increasing use or change of function of structures, etc.) and degradation (corrosion of steel reinforcement, alkali silica reaction, etc.). On the other hand, confinement of concrete is an efficient technique to increase the load carrying capacity and ductility of concrete members primarily subjected to compression. By providing lateral confining pressure, the concrete is subjected to a tri-axial state of stress, so that the compressive strength and deformability increase. Since the introduction of FRP as externally bonded reinforcement, confinement by means of FRP wrapping has been of considerable interest for upgrading columns, piers, chimneys, etc. and several research programs have been conducted internationally.

To verify the effectiveness of FRP confinement with respect to real-scale axially loaded columns and to investigate some specific aspects of the modeling of FRP confined concrete, compression tests on large-scale columns wrapped with FRP have been performed (Matthys 2000). The variables considered in this test program included FRP type, full or partial wrapping, and fibre orientation (circular or helicoidal). This research mainly focuses on the experi-

mental and analytical work concerning large-scale axially loaded columns, confined with external FRP wrapping reinforcement. The study also looks into the strength modeling of FRP confined concrete, i.e. the effective circumferential FRP failure strain and the effect of increasing confining action.

2 EXPERIMENTAL PROCEDURE

Eight large-scale columns were manufactured. The confined-concrete columns were subjected to axial loading. The test parameters of the wrapped columns are given in Table 1a, b. The columns had a total length of 2 m, a longitudinal steel reinforcement ratio of 0.9% and 8 mm diameter stirrups spaced every 140 mm. Extra stirrup reinforcement was provided at the column ends. All columns have a 400 mm circular cross-section. Except for columns K6 and K7, the FRP is applied over the total area (full wrapping) in a circular way, providing 200 mm overlap length in the circumferential direction (no overlap was provided in the longitudinal direction). For columns K6 and K7 partial wrapping is applied, either in a circular way with a clear spacing of 200 mm (K6) or in a helicoidal way with a pitch of 400 mm and a clear spacing of 200 mm (K7).

Table 1a. Test parameters of wrapped columns.

Spec.	Column diameter	Concrete	
		Age at test	f'_c (28 days)
	[mm]	[days]	[N/mm ²] ⁽¹⁾
K1	Ø 400	29	31.8
K2	Ø 400	28	34.3
K3	Ø 400	29	34.3
K4	Ø 400	29	39.3
K5	Ø 400	32	39.3
K6	Ø 400	28	35.8
K7	Ø 400	28	35.8
K8	Ø 400	32	39.1

⁽¹⁾ N/mm² = MPa

Table 1b. Test parameters of wrapped columns.

Spec.	FRP Confinement					
	FRP type	No. of layers	Width	Clear spacing	Pitch	Wrapping
	[mm]		[mm]	[mm]	[mm]	[mm]
K1	-	-	-	-	-	-
K2	C240	5	300	0	0	full
K3	C640	4	300	0	0	full
K4	TU600/25	6	200	0	0	full
K5	TU600/25	2	200	0	0	full
K6	TU600/25	4	200	200	0	partial
K7	TU600/25	4	200	200	400	partial
K8	TU360G160C/27G	4	50	0	0	full

Different types of FRP reinforcement consisting of CFRP sheets (C240 and C640), GFRP fabrics (TU600/25) and HFRP (hybrid FRP) fabric (TU360G160C/27G) have been used to confine the concrete columns. Tensile tests (according to ASTM D3039/D3039M) were performed on FRP sheet specimens with a width of 50 or 100 mm. Results of the tensile tests of the FRP sheets and the longitudinal steel rebars and stirrups are reported in terms of mean values in Table 2a, b.

The concrete columns were subjected to an axial load test in a compression testing machine with a capacity of 10000 kN. The load was applied in a displacement controlled mode at 0.5 mm/min. Due to problems with the loading control unit, the displacement rate of column K2 decreased after reaching maximum load. Axial and circumferential deformations of the columns were measured both manually and electronically. Manual measurements comprised dial gauges with a gauge length of 1 m and mechanical deformeters with a gauge length of 200 mm or 50 mm. For the electronic measurements,

both strain stirrups (gauge length 200 mm or 80 mm) and strain gauges have been used.

Table 2a. Mean tensile properties obtained by tensile testing.

Type	Nominal Dimensions	Yield strength
	(mm)	(N/mm ²)
Steel Rebar S500 ⁽¹⁾	Ø 8 Ø 12	560 620
C-sheet 240 - Multipox T	300 x 0.117 ⁽²⁾	-
C-sheet 640 - Multipox T	300 x 0.235 ⁽²⁾	-
TU600/25 - PC5800	200 x 0.300 ⁽²⁾	-
TU360G160C/27G-PC5800	50 x 0.123 ⁽²⁾	-

⁽¹⁾ Characteristic yield strength value equal to 500 N/mm²⁽²⁾ Equivalent dry-fibre thickness

Table 2b. Mean tensile properties obtained by tensile testing.

Type	Tensile Strength	Ultimate strain	E-modulus
	(N/mm ²)	(%)	(N/mm ²)
Steel Rebar S500 ⁽¹⁾	610 720	2.77 8.73	200000 200000
C-sheet 240 - Multipox T	2600	1.19	198000
C-sheet 640 - Multipox T	1100	0.22	480000
TU600/25 - PC5800	780	1.30	60000
TU360G160C/27G-PC5800	1100	0.96	120000

3 EXPERIMENTAL TEST RESULTS

3.1 Behaviour at ultimate load

The test results of the columns in terms of maximum load Q_{max} , axial stress (maximum load Q_{max} / gross column section A_g), strength increase, axial (ϵ_{c1} and ϵ_{cu}) and circumferential strains (ϵ_{cf1} and ϵ_{cfu}) at maximum and ultimate load respectively and ratio of the circumferential strain ϵ_{cfu} over the FRP failure strain ϵ_{fu} are given in Table 3a, b. The mentioned strains are the mean values of the strain gauge measurements.

Table 3a. Test results of compression tests on columns.

Specimen	Q_{max}	Q_{max}/A_g	Q/Q_{ref}
	[kN]	[N/mm ²]	[-]
K1 (Ø/Ref.)	4685	37.3	1.00
K2 (Ø/C240/#5/full)	7460	59.4	1.59
K3 (Ø/C640/#4/full)	7490	59.6	1.60
K4 (Ø/G/#6/full)	7580	60.3	1.62
K5 (Ø/G/#2/full)	5325	42.4	1.14
K6 (Ø/G/#4/partial-circ.)	5000	39.8	1.07
K7 (Ø/G/#4/partial-helic.)	4810	38.3	1.03
K8 (Ø/H/#4/full)	6230	49.6	1.33

Table 3b. Test results of compression tests on columns.

Specimen	ϵ_{c1}	ϵ_{cu}	$\epsilon_{c/1}$	$\epsilon_{c/n}$	$\epsilon_{c/n}/\epsilon_{fu}$
	[mm/m]	[mm/m]	[mm/m]	[mm/m]	[-]
K1 (Ø/Ref.)	2.8	3.1 ⁽¹⁾	1.7	1.8 ⁽¹⁾	-
K2 (Ø/C240/#5/full)	11.1	(12.0) ⁽²⁾	6.9	(7.3) ⁽²⁾	(0.61) ⁽²⁾
K3 (Ø/C640/#4/full)	4.3	4.3	2.5	2.5	1.14
K4 (Ø/G/#6/full)	6.9	6.9	7.5	7.5	0.58
K5 (Ø/G/#2/full)	3.8	3.8	6.8	8.0	0.62
K6 (Ø/G/#4/partial-circ.)	2.8	3.3	1.6	3.3	0.25
K7 (Ø/G/#4/partial-helic.)	2.2	2.2	3.1	3.3	0.25
K8 (Ø/H/#4/full)	5.9	6.0	5.3	5.3	0.55

⁽¹⁾ Test stopped at an axial strain of about 3.1 mm/m.

⁽²⁾ Problems with the load control unit of the actuator in the post peak region.

The unconfined ultimate compressive strength of the control column (K1) was 37.3 MPa. A strength increase up to 1.62 is found for the different columns and strongly depends on the wrapping lay-out, and FRP type and amount. The confined concrete columns failed by fracture of the FRP reinforcement, as shown in Figure 1. For the fully wrapped circular columns at ultimate load, when confinement action was no longer provided due to FRP fracture, the internal steel started buckling and the crushed concrete fell down between the fractured FRP. For the partially wrapped columns it was noted that the unconfined zones started crushing when reaching the strength of the plain concrete. For these columns, buckling of the internal steel occurred in the unconfined zones, after FRP failure.



Figure 1a. Failure of HFRP fully wrapped column.



Figure 1b. Failure of GFRP partially wrapped column.

Figure 1. Failure aspect of the confined columns.

Results show that the strength increase basically depends on the amount and tensile strength of the FRP wrapping. The higher the axial stiffness of the FRP wrapping, the lower the ultimate axial strain and hence the lower the increase in ductility. The ratio $\epsilon_{lu}/\epsilon_{fu}$ (circumferential ultimate strain/ultimate strain of the fiber) for fully wrapped circular columns (except for K3) was between 0.55 and 0.62 as shown in Table 3b. This may indicate that secondary effects near failure, such as stress concentrations in the FRP due to non-homogeneous deformations of the damaged concrete are significant. This may have led to a non-uniform distribution of the strain in the FRP wrapping. It should be noted that the ultimate tensile failure strain (ϵ_{fu}) reported by the manufacturer was much higher than the mean strain value obtained in this study. The ultimate failure strain reported by the manufacturer was 0.4%.

Comparing fully and partially wrapped columns with the same type and total amount of FRP (Table 3a, b), less efficiency is obtained in case of partial wrapping as part of the concrete is unconfined. Furthermore, helicoidal wrapping results in a lower strength increase and axial strain compared to circular wrapping. This is due to the fact that the fibres are no longer aligned in an optimum way to restrain the lateral expansion of the concrete. The ratio $\epsilon_{lu}/\epsilon_{fu}$ obtained for the partially wrapped columns (K6 and K7) equals 0.3, which is much lower than the fully wrapped circular columns.

3.2 Effective FRP strain coefficient

According to the obtained test results, the mean effective FRP failure strain (circumferential failure strain, ϵ_{lu}) when reaching the ultimate state of the wrapped members is lower than the ultimate FRP

strain $\varepsilon_{fu} = f_f/E_f$. The ratio of the circumferential strain at failure to the ultimate tensile strain of the FRP is referred to, as the effective FRP strain coefficient ($\beta = \varepsilon_{lu} / \varepsilon_{fu}$). Thus, the maximum lateral confinement pressure f_{lu} is given as:

$$f_{lu} = K_{conf} \frac{\beta \cdot f_f}{E_f} \quad (1)$$

For fully wrapped circular cross-sections K_{conf} is given by

$$K_{conf} = \frac{2t_f E_f}{D} \quad (2)$$

where E_f is the elastic modulus of the FRP composite, f_f is the ultimate strength of the FRP composite, t_f is the thickness of the fiber and D is the diameter of the unconfined concrete.

To quantify the effective FRP strain coefficient (β), using the results of this study and others (Picher 1996, Watanable 1997, Mirmiran 1998, Matthys 1999, Toutanji 1999, Xiao 2000, Pessiki 2001), the coefficient (β) was expressed as a function of the parameter K_{conf} , as shown in Figure 2. For the purpose of obtaining a simple design equation for the lateral confinement pressure, the value β is set to be equal to 0.6. As shown in Figure 2 the effective FRP strain coefficient β , decreases with increasing the stiffness of the fiber. This implies that the value of β for CFRP is lower than that for GFRP, since carbon fiber has higher stiffness than glass fiber. This is in agreement with a study conducted by Lam & Teng (2003), which showed that β equal to 0.583 for CFRP-confined concrete cylinders and 0.669 for GFRP-confined concrete cylinders.

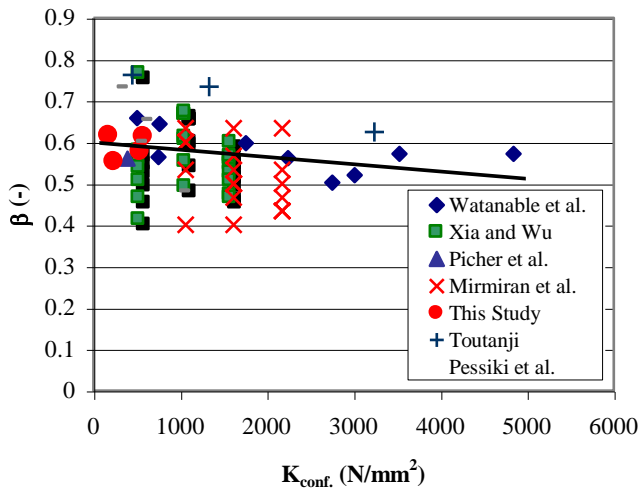


Figure 2. Effective FRP failure strain.

As β is related to f_f/E_f , the strength and stiffness of the FRP should be known. Because the characterization of the tensile properties of FRP is influenced by the way of testing, the tensile strength of the FRP should be determined in accordance with ASTM D3039/D3039M or similar method using flat coupons.

3.3 Strength models of FRP-confined concrete

Most of the existing strength models adopted the concept of Richart et al. (1929), in which the strength at failure for concrete confined by a hydrostatic fluid pressure takes the form:

$$f'_{cc} = f'_{co} + k_1 f_l \quad (3)$$

where f'_{cc} is the maximum strength of the confined concrete, f'_{co} is the maximum strength of the unconfined concrete, f_l is the lateral confining pressure, and k_1 is a confinement effectiveness coefficient.

A number of strength models have been proposed specifically for FRP-confined concrete. These models use Eq. (3) with a modified expression for k_1 . Based on regression analysis, an equation for k_1 was obtained by Toutanji (1999). When k_1 is substituted in Eq. (3), an expression to calculate the ultimate confining stress of FRP-confined concrete is obtained:

$$f'_{cc} = f'_{co} \left[1 + 3.5 \left(\frac{f_l}{f'_{co}} \right)^{0.85} \right] \quad (4)$$

where f_l

$$f_l = \frac{2t_f E_f \varepsilon_l}{D} \quad (5)$$

Experimental data presented in this study and others (Lam & Teng 2003) have shown that the circumferential failure strain is mostly smaller than the ultimate strain obtained from standard tensile testing of the FRP reinforcement. As shown earlier, the effective FRP strain coefficient ($\beta = \varepsilon_{clu} / \varepsilon_{fu}$), was expressed as a constant and equal to 0.6.

Based on this finding, Toutanji's model (1999) was modified to account for the reduction in the lateral confinement stress. Thus, the lateral confining stress becomes:

$$f_l = \frac{2t_f E_f \varepsilon_{clu}}{D} \quad (6a)$$

$$\varepsilon_{clu} = \beta \varepsilon_{fu} \quad (6b)$$

Using a reduction factor β of 0.6 and substituting f'_l into Eq. (1), the revised Toutanji's model to predict the ultimate axial compressive strength of FRP-confined concrete columns then can be given by the formula:

$$f'_{cc} = f'_{co} \left[1 + 2.3 \left(\frac{\bar{f}'_l}{f'_{co}} \right)^{0.85} \right] \quad (7a)$$

where

$$\bar{f}'_l = \frac{2t_f E_f \varepsilon_{fu}}{D} \quad (7b)$$

where ε_{fu} is the ultimate tensile strength of the FRP.

A comparison between the ultimate strength predicted by various models and the experimental ultimate strength values is shown in Figure 3. Considerable similarities were found between the different models. However, the best predictions were found in models by Miyauchi et al. (1999), Saafi et al. (1999), Samaan et al. (1999), and Toutanji Revised. As expected, the model by Mander et al. (1988) tends to overestimate the ultimate strength. This model was developed for confining concrete under triaxial compression with equal lateral effective confining stress by steel spirals or circular hoops.

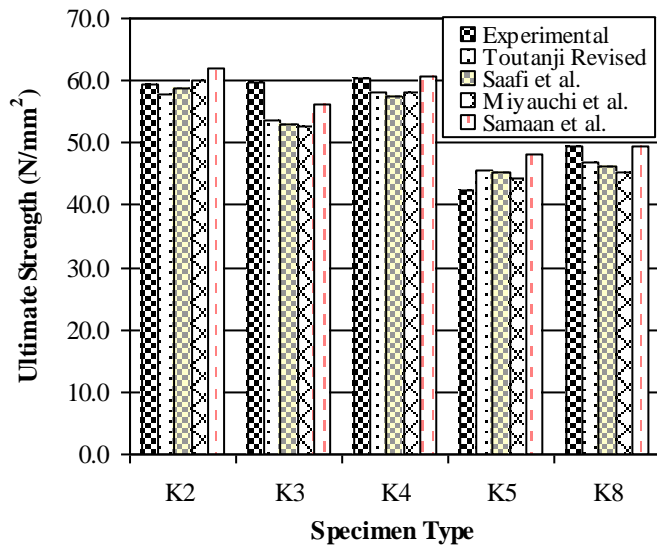


Figure 3. Comparison between the experimental values and those predicted by different models.

4 CONCLUSIONS

Confinement of concrete by means of FRP wrapping is an efficient technique to increase strength and ductility. The quality of execution and the wrapping configuration have a considerable influence on the effectiveness of the FRP wrapping. Beside the effectiveness (influence of partial wrapping and fibre orientation), the strength increase basically depends on the amount and tensile strength of the FRP wrapping. The increase in ductility (ultimate axial strain) is inversely proportional to the stiffness (E-modulus) of the FRP wrapping. Hence, for a given type of FRP, the higher the strength increase the lower the increase in ductility.

Due to several influencing factors, among which the local stress concentrations near failure, a reduced mean FRP failure strain is found for the wrapped specimens. To model this aspect, a reduction coefficient was introduced, referred to as the effective FRP strain coefficient ($\beta = \varepsilon_{lu}/\varepsilon_{fu}$), which is equal to 0.6. Because the characterization of the tensile properties of FRP is influenced by the way of testing, the tensile strength of the FRP should be determined in accordance with ASTM D3039/D3039M or similar method using flat coupons.

Four models, by Miyauchi et al. (1999), Saafi et al. (1999), Samaan et al. (1999), and Toutanji Revised, were found to predict the ultimate strength of FRP-confined concrete quite accurately. Results show that the predicted ultimate strengths compare well with those of experimental.

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