Confinement of Axially Loaded Concrete Columns with FRP Wrapping

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Summary

Confinement is generally applied to compressed concrete members, with the aim of enhancing their load carrying capacity or to increase their ductility, particularly in the case of seismic upgrading. At the Magnel Laboratory for Concrete Research, an extensive test programme was carried out, consisting of compression tests on 15 cylinders with a height of 300mm and 11 full scale columns all strengthened with FRP, to study the structural behaviour of FRP confined concrete columns. On the basis of these test results, an evaluation of different influencing factors is made. An analytical verification of six existing models for the maximum strength and the stress-strain behaviour was performed.

Keywords: concrete columns; confinement; fiber reinforced polymer (FRP)

1. Introduction

Generally, concrete columns have an important function in the structural concept of many structures. However, quite often, these structures are vulnerable to exceptional actions (such as impact or seismic loads), increase of required load bearing capacity (increasing use or change of function of structures, etc.) and possible degradation (corrosion of steel reinforcement, alkali-silica reaction, etc.). By providing confinement to the concrete, fiber reinforced polymers (FRP) are increasing both strength and ductility of concrete columns and they also prevent buckling of longitudinal reinforcement. The FRP jackets are made of sheets wrapped around the concrete column in one or more layers in order to obtain the required thickness. The main advantages of composite materials over other materials are: high strength-to-weight ratio, small thickness, which makes transportation and application easier, and resistance to corrosion.

At the Magnel Laboratory for Concrete Research a test programme was set up to study these specific aspects and parameters affecting the confinement of concrete columns with FRP, focussing on uniaxial compression of small and large scale specimens [1].

2. Experimental Programme

2.1. Tensile tests on FRP

Different types of FRP sheets were used in the test programme: two types consisting of carbon fibres (CFRP), one unidirectional sheet with a high modulus of elasticity (C640) and one unidirectional sheet with a lower modulus of elasticity (C240); one bidirectional type consisting of glass fibres (GFRP) and one bidirectional hybrid type consisting of a mixture of carbon and glass fibres (HFRP) in the longitudinal direction and glass fibres in the transverse direction. Tensile tests were performed on single layer, impregnated and straight FRP specimens with a width of 50 mm and a free length of 500 mm. The anchorages were provided by means of bonded steel plates in order to avoid local damage to the sheets. Table 1 gives a survey of the main experimental properties of the different types of FRP reinforcement which have been used and are based on the results of three tensile tests.

Table 1 Properties of FRP wrapping reinforcement – tensile tests

FRP type	Epoxy adhesive	Nominal thickness [mm]	Tensile strength [MPa]	Failure strain [mm/m]	Tangent E-mod. [MPa]
CFRP-C640 Unidirectional dry-fibre sheet	Multipox T	0.235	1100	2.2	420000
CFRP-C240 Unidirectional dry-fibre sheet	Multipox T	0.117	2600	11.9	200000
GFRP –TU600/25 Bidirectional dry-fibre fabric	PC5800	0.300	800	13.5	60000
HFRP-TU360G160C/27G Bidirectional dry-fibre fabric	PC5800	0.123	1100	9.6	85000

In table 1, reference is made to the nominal thickness of the FRP reinforcement, equalling the effective fibre thickness (fibre areal weight divided by fibre density).

2.2. Uniaxial compression tests on wrapped cylinders

For both types of CFRP reinforcement, compression tests were performed on standardized cylinders (diameter 150 mm, height 300 mm) circularly wrapped with one layer of FRP, providing a sufficient overlap length (150 mm). Impregnation and bonding were applied 7 days before the loading tests, which were normally performed at a concrete age of 28 days. The FRP reinforcement is either bonded (b) or not bonded (nb) to the concrete. The latter case is achieved by gluing a thin aluminium foil to the concrete before FRP application. Table 2 gives the obtained test results for the reference cylinders and the FRP types C240 and C640 in terms of ultimate strength and strains (mean value of three tests). The specimens failed by fracture of the FRP reinforcement. In table 2 positive deformation values correspond to shortenings.

Table 2 Compression tests on wrapped cylinders

Specimen	Strength [MPa]	Strength increase [-]	Ultimate axial strain [mm/m]	Ultimate circumf. strain [mm/m]
Reference	34.9	1.00	2.1	-1.2
C240 b	46.1	1.32	9.0	-12.6
C240 nb	42.2	1.21	7.2	-10.8
C640 b	45.8	1.31	6.0	-3.1
C640 nb	40.7	1.17	3.6	-1.8

From these test results, the following is concluded [2]:

- Almost the same strength increase is found for cylinders wrapped with FRP types C240 and C640.
- A strength increase between 1.17 and 1.32 is obtained. The strengthening effect is influenced by the bonding between the wrapping and the concrete.

2.3. Uniaxial tests on large-scale columns

Large-scale confined columns were subjected to uniaxial loading. These columns had a total length of 2 m, a longitudinal steel reinforcement ratio of 0.9 % and 8 mm diameter stirrups with a spacing of 140 mm. Extra stirrups were placed at the ends of the columns over a depth of 350 mm. In table 3 a survey of the tested columns is given. The corners of the square and rectangular sections were rounded with a radius of 30 mm or 15 mm (designations r30 and r15 in the second column of table 3). Impregnation and bonding were applied 7 days before the loading tests, which were normally performed at a concrete age of 28 days. The mean cylinder strength for the columns is 37.2 N/mm².

Table 3 Survey of the tested columns

Col.	Col. Size [mm]	f_{co} [a] [MPa]	FRP type	# layers	Width [mm]	Clear spacing [mm]	Pitch [mm]	Wrapping
1	ϕ 400	31.8	-	-	-	-	-	-
2	ϕ 400	34.3	CFRP-C240	5	300	0	0	Full
3	ϕ 400	34.3	CFRP-C640	4	300	0	0	Full
4	ϕ 400	39.3	GFRP	6	200	0	0	Full
5	ϕ 400	39.3	GFRP	2	200	0	0	Full
6	ϕ 400	35.8	GFRP	4	200	200	0	Partial
7	ϕ 400	35.8	GFRP	4	200	200	400	Partial
8	ϕ 400	39.1	HFRP	4	50	0	0	Full
9	355x355/r30	39.1	GFRP	2	200	0	0	Full
10	355x355/r15	37.7	GFRP	2	200	0	0	Full
11	250x500/r30	37.7	GFRP	2	200	0	0	Full

[a] : unconfined concrete strength measured on test cylinders with a diameter of 150mm and a height of 300mm

The test results of the columns are given in table 4 in terms of failure load Q_u, the maximum load Q_{cc}, maximum stress Q_{cc} /A, strength increase, axial and circumferential strains at failure. All the confined columns failed by fracture of the FRP confining reinforcement. In some cases this occurred after the peak load Q_{cc} was reached.

Table 4 Uniaxial compression tests on columns

Col.	Q_{cc} [kN]	Q_u [kN]	Q_{cc}/A [N/mm²]	Strength increase	Axial strain [mm/m]	Circumf. Strain [mm/m]
1	4685	4685	37.3	1.00	3.1	-1.7
2	7462	7462	59.4	1.59	11.1	-6.9
3	7460	7460	59.4	1.59	4.3	-2.5
4	7580	7580	60.3	1.62	6.8	-7.3
5	5325	5177	42.4	1.14	3.8	-8.0
6	5000	4700	39.8	1.07	3.2	-4.5
7	4810	4612	38.3	1.03	2.2	-3.7
8	6230	6230	49.6	1.33	5.9	-5.2
9	5810	5810	46.2	1.24	5.1	-2.1
10	5140	5054	40.9	1.10	4.1	-3.5
11	4990	4990	39.7	1.06	1.8	-0.9

The columns 2, 3, 4 and 8 are fully wrapped with a different type of FRP, with approximately the same expected ultimate strength (except for column 8). The expected strength is based on models described in the literature. From these tests the following is noted:

- Both strength and ductility increase are obtained for the wrapped columns.
- Higher stiffness of the FRP confinement results in a lower ductility.
- A similar strength increase (about 60 %) is obtained for the columns 2, 3 and 4.
- Compared to the wrapped cylinders, lower mean circumferential strains at ultimate were found. This may be due to size effects when applying multiple layers.

Columns 4 and 5 are fully wrapped with a different amount of GFRP (column 4 with 6 layers, column 5 with 2 layers). Table 4 shows that, although the strength increase for column 5 is rather small, there is a ductility increase in comparison with the reference column. For an increasing number of layers, the ultimate circumferential strain decreases, showing that the FRP reinforcement is less effective.

Column 5, 6 and 7 have the same amount of external reinforcement, but each one is differently wrapped. Column 5 is fully wrapped with two layers, column 6 is wrapped with horizontal bands and column 7 is spirally wrapped, each with four layers. The three columns are reaching approximately the same maximum strength, although the ductility differs. Full wrapping appears to be more efficient than circular wrapping, which is more efficient than spiral wrapping.

The cross-section of columns 5, 9 and 11 was respectively circular, square and rectangular, having approximately the same surface. The square and rectangular section had the same radius of corner rounding i.e. 30 mm. These columns were fully wrapped with 2 layers of GFRP. Following the test results, the wrapping is more efficient with respect to ductility and ultimate strength as the cross-section approaches the circular section.

The radius of the corners of columns 9 and 10 is respectively 30 mm and 15 mm. From the test results, it can be noted that the ultimate strength and ductility increase as the radius of the corners increases. This confirms the assumption that the FRP reinforcement on rectangular sections mainly works on the corners, having a larger working area for the confining pressure when the radius of the corners increases.

3. Analytical verification of models

The analytical verification was performed for the fully wrapped columns with a circular cross-section. The verification is based on the tensile strength obtained from the tensile tests and is performed for 6 models, found in literature (Table 5). The models set up by Mander et al. [3,4] and the model described in the Model Code 90 [5] are considering steel-confined concrete. Models for FRP confinement were proposed by Monti et al. [6], Mirmiran et al. [7] and Toutanji [8]. Monti et al. have proposed an iterative approach, based on the model of Mander et al., to predict the stress-strain behaviour, taking into account the increasing confining action.

Table 5 Analytical verification

Specimen	Exp. Q_u [kN]	f_l / f_{co}	Analytical : $Q_{u,calc}$ / $Q_{u,exp}$					
			Mander	MC90	Iterative model	Monti	Mirmiran	Toutanji
C240 b	814	0.12	1.15	1.18	1.08	0.93	1.10	1.18
C240 nb	746	0.12	1.25	1.29	1.18	1.01	1.20	1.29
C640 b	809	0.10	0.97	1.14	1.23	0.87	1.07	1.13
C640 nb	719	0.10	1.09	1.28	1.38	0.98	1.21	1.27
2	7462	0.22	1.11	1.21	1.13	1.02	1.08	1.22
3	7460	0.15	0.82	1.06	1.12	0.88	0.98	1.07
4	7580	0.18	1.14	1.26	1.21	1.05	1.15	1.27
5	5325	0.06	1.31	1.38	1.24	1.03	1.35	1.35
8	6230	0.07	1.13	1.19	1.10	0.89	1.13	1.18
Mean			1.11	1.22	1.19	0.96	1.14	1.22
Standard deviation			0.14	0.09	0.09	0.07	0.11	0.09

On the mean, all verified models give overestimations of 10 to 20 % of the magnitude of the failure load, the model of Monti giving the mean value closest to one. Due to the use of the ultimate stress and strain of the FRP obtained from tensile tests on straight specimens, an overestimation of the ultimate strength is to be expected.

4. Conclusions

Confinement of concrete by means of FRP wrapping is an efficient technique to increase both strength and ductility. An extensive test programme was carried out, consisting of tensile tests on CFRP, GFRP and HFRP; and tests on cylinders and full scale columns. On the basis of these test results, an evaluation of the influence of the type of FRP, the amount of external reinforcement, partial or full wrapping, the shape of the cross-section, the radius on the corners of square sections and bonded or unbonded wrapping is made.

An analytical verification of six existing models was performed. Distinction is made between models for steel confinement and models for FRP confinement. The model of Monti et al. gives a mean value closest to 1 for the fully wrapped specimens. The other models are overestimating the test results.

5. References

[1] MATTHYS, S., Structural behaviour and design of concrete members strengthened with externally bonded FRP reinforcement, Doctoral thesis, Ghent University, 2002

[2] MIRMIRAN, A., SHAHAWY, M., SAMAAN, M., EL ECHARY, H., MASTRAPA, J.C., PICO, O. "Effect of column parameters on FRP-confined concrete", *ASCE Journal of Composites for Construction*, Vol. 2, No. 4, Nov. 1998, pp 175-185

[3] MATTHYS, S., TAERWE, L., AUDENAERT, K. "Tests on axially loaded columns confined by FRP sheet wrapping", *proceedings of the fourth International Symposium on FRP for Reinforced Concrete Structures (FRPRCS-4),* ACI-Convention, Baltimore (USA), 1999

[4] MANDER, J.B., PRIESTLEY, M., PARK, R."Theoretical stress-strain model for confined concrete", *ASCE Journal of Structural Engineering*, Vol. 114, No. 8, 1988, pp 1804-1826

[5] MANDER, J.B., PRIESTLEY, M., PARK, R. "Observed stress-strain behaviour of confined concrete", *ASCE Journal of Structural Engineering*, Vol. 114, No. 8, 1988, pp 1827-1849

[6] CEB-FIB Model Code 90, pp 101-106

[7] SPOELSTRA, M., MONTI, G. "FRP-confined concrete model" *ASCE Journal of Composites for Construction*, Vol. 3, No. 3, Aug. 1999, pp 143-150

[8] SAMAAN, M., MIRMIRAN, A., SHAHAWY, M. "Model of concrete confined by fiber composites", *ASCE Journal of Structural Engineering*, Vol. 124, No. 9, Sept. 1998, pp 1025-1031

[9] TOUTANJI, H. "Stress-strain characteristics of concrete columns externally confined with advanced fiber composite sheets", *ACI Materials Journal*, Vol. 96, No. 3, 1999, p397-404