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Concrete-Filled Fibre Reinforced Plastic Circular Columns

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Summary

An experimental investigation was conducted to determine the strength enhancement of concrete columns due to confinement provided by filament wound glass fibre tubes used as permanent formwork. The principal variables were concrete strength, slenderness and angle of fibre alignment. Significant increases in compressive strength were achieved. A design approach has been proposed which uses existing design equations, modified to reflect the increased confidence in the effective compressive strength of concrete.

1. Introduction

Research has shown that Fibre-Reinforced Plastics (FRP) reinforcement can successfully be used as the tensile component to reinforce concrete beams in bending [1]. However, their use as longitudinal reinforcement in compression members is not economic due to the relatively low compressive modulus and strength of FRP composites [2]. The purpose of the research described in this paper is to investigate the use of FRP composites as confinement reinforcement for concrete. Experimental work into the behaviour of confined concrete has shown that there is a significant increase in both strength and ductility of the concrete. This form of construction offers additional advantages since the FRP composite serves as permanent formwork and provides a barrier against aggressive agents, thus improving the column's durability. Using the FRP composite as peripheral reinforcement for circular columns results in the FRP composite acting in direct tension to develop the confining hoop stress.

Previous researchers have examined the enhanced properties of concrete cylinders confined by FRP composite wraps, and a number of empirical design equations have been proposed [3-5]. These design equations are based on experimental work using small specimens and the results cannot be taken as representative of the behaviour of realistically sized columns. To investigate the behaviour of full scale concrete columns confined with FRP composites, an extensive test programme is being under taken at the University of Southampton. Additionally, ten large diameter columns were tested in collaboration with the Building Research Establishment. The preliminary results of part of this test programme are presented in this paper.

2. Experimental Programme

2.1 Materials

2.1.1 Concrete

One of the primary objectives of the test programme is to investigate the influence of concrete strength. Two different concrete mixes were designed to have compressive cube strengths of 25 N/mm^2 and 35 N/mm^2. All the tubes were cast in the vertical position as would normally be the case in construction. The concrete was dropped into the tube from the top, and vibrated internally by a poker vibrator. To minimise segregation of the concrete, a cohesive concrete was used with a slump of 50mm.

2.1.2 Filament Wound Tubes

The filament wound tubes were supplied by Fibaflo Plastic Ltd. The tubes consist of 51% continuous E-glass fibres by volume, embedded in an epoxy resin. The tensile strength of the basic E-glass fibre is 3400 N/mm^2 with an elongation of 4.5% at failure [6].Three different nominal angles of fibre alignment were tested; 90°, 67.5° and 45°, the angle of fibre alignment being measured from the longitudinal axis. Limitations imposed by the filament winding machinery meant that the actual winding angles differed from the nominal values. The properties of the tubes are shown in Table 1. The theoretical confining pressure is given by Equation 1:

$$f_{lat} = \frac{2t}{D} v_f \sigma_f \sin^2 \alpha \qquad \text{Equation 1}$$

Diameter ϕ mm	Standard Deviation mm	Thickness t mm	Standard Deviation mm	Fibre Alignment α degrees	Confining Pressure f_{lat} N/mm^2
59.86	0.21	2.53	0.14	75.5	137.38
79.85	0.09	2.46	0.11	78.1	102.30
79.89	0.04	2.48	0.11	57.8	77.08
79.89	0.07	2.66	0.15	43.4	54.51
99.97	0.09	2.45	0.13	80.4	82.63
100.02	0.10	2.28	0.14	71.4	71.01
100.03	0.05	2.22	0.10	49.9	45.03
300.10	0.09	3.80	0.11	86.8	43.78
399.88	0.21	5.07	0.09	87.6	43.89

Table 1 Dimensions of filament wound tubes

2.2 Experimental Procedure

Tests at the University of Southampton were carried out on either a 2000 kN Losenhausen or 1500 kN Instron column rig. Both machines were operated in position-control for safety reasons due to the brittle failure mechanism of the specimens. The additional tests at the BRE were carried out on their 10000 kN load-controlled Amsler column rig.

2.2.1 Axially Loaded Columns

The columns were tested in axial compression to failure. Measurements consisted of load, crosshead displacement, axial and circumferiental strain. Axial strains were measured over the middle half of their length using an extensometer, consisting of four LVDT's positioned at four orthogonal points. The extensometer was removed at an axial strain of 2% to prevent damage to the instrumentation and to eliminate any additional confinement induced by the extensometer. The circumferential expansion of the cylinders was determined by an LVDT attached to the end of a sheathed cable positioned at mid-height around the periphery of the cylinder.

The columns were loaded in equal displacement increments of 0.001mm/min/ mm length of sample. Readings were taken automatically using an Amplicon PC226 data acquisition board in a Pentium PC. To minimise errors due to fluctuations in the electrical supply, a filtered power supply was used and each reading consisted of an average 1000 samples taken over one second.

2.2.2 Eccentrically Loaded Columns

Two column lengths were investigated with length/diameter ratios of 5 and 10. The columns were tested to failure under eccentric compression. All loading was of short duration; the effects of sustained or repeated loading were not investigated. Measurements consisted of load, crosshead displacement, lateral deflection at mid and quarter heights, and both axial and circumferential strains. The eccentricity of all the columns was 5% of the internal diameter. The load was applied by increasing the platen displacement in equal increments determined from the cylinder tests. Each test to failure lasted approximately 50 minutes.

3. Experimental Results and Discussion

3.1 Axially Loaded Columns

Table 2 gives the strength and deformation at failure for the confined columns. The strength clearly increases as the orientation of the fibres approaches the hoop direction. Figure 1 shows the stress-strain curve for the 80mm diameter specimens. The shape of the curves is initially similar to plain concrete, and once the unconfined concrete strength is exceeded the curve continues in a linear manner with a reduced slope. The stiffness of the secondary slope is a function of the orientation of the fibres, with the stiffness increasing as the fibres angle of wind approaches the hoop direction. Ultimate failure was achieved for all the specimens except fw112 and fw113. However, creep failure of specimen fw112 was achieved under a sustained load of 10140 kN for 6 minutes.

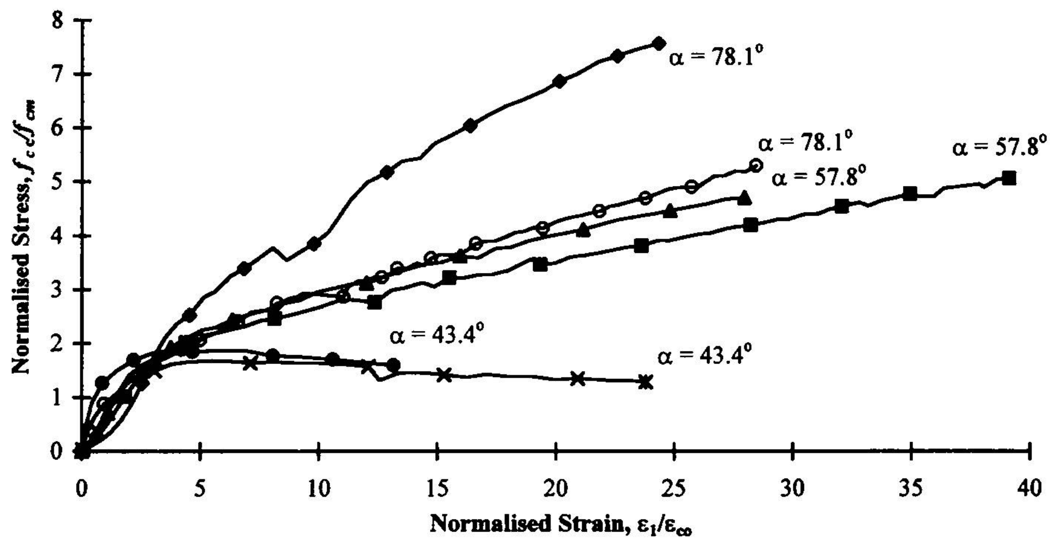

Fig 1 Stress- Strain Relationship for Axially Load Columns

The orientation of the fibres was also found to influence the failure mechanism of the cylinders. Cylinders where the fibres are aligned at angles close to the hoop direction failed by fibres rupturing then unwrapping about the middle third of the specimen. Fibre orientation of approximately 67.5° caused a tensile rupture of the fibres along the entire length of the cylinder. Cylinders with fibres at approximately 45°, resulted in a compressive failure mode of the fibres.

The measured circumferential strains are significantly less than the theoretical rupture strain of the basic fibre. This corresponds with observations during testing where the large axial deformations resulted in premature tensile failure of the fibres, due to localised compression. Consequently, the theoretical confining pressure of the fibres is not achieved, with an increasing reduction as the winding angle reduced.

The degree of compressive strength enhancement is a function of both the confining pressure and unconfined strength of concrete. It was found that the lower strength concrete exhibited a greater increase in compressive strength and ductility. In general, lower strength concrete is more ductile and the proportionately greater lateral expansion results in larger confining pressures.

Ref. No.	Diameter ϕ mm	Fibre Alignment	Failure Load kN	Failure Stress, f_{cc} N/mm^2	f_{cc}/f_{cu}	Axial Strain %	Circumferential Strain %
fw1	59.86	75.5	445.4	158.3	7.40	4.46	-1.25
fw2	59.86	75.5	416.2	147.9	5.44	4.05	-1.16
fw7	79.85	78.1	888.6	177.4	7.57	4.87	-1.63
fw8	79.85	78.1	934.3	186.6	5.30	5.70	-1.57
fw15	79.89	57.8	572.1	114.1	5.06	7.83	-4.98
fw16	79.89	57.8	775.1	154.6	4.71	5.60	-3.08
fw23	79.89	43.4	248.9	49.7	1.68	1.90	-1.21
fw24	79.89	43.4	234.0	46.7	1.49	1.14	-1.47
fw31	99.97	80.4	973.1	124.0	6.30	3.78	-1.29
fw32	99.97	80.4	1129.4	143.9	3.95	3.17	-1.23
fw39	100.02	71.4	913.9	116.3	4.13	5.41	-3.42
fw40	100.02	71.4	820.7	104.5	4.08	2.02	-3.37
fw47	100.03	49.9	458.5	58.3	1.87	-	-
fw48	100.03	49.9	414.9	52.8	2.14	-	-
fw107	300.10	86.8	5980	84.5	3.49	2.58	-1.40
fw108	300.10	86.8	6050	85.5	2.46	2.13	-1.32
fw112	399.88	87.6	10140	80.7	3.27	2.41	-1.15
fw113	399.88	87.6	9750	77.6	2.13	1.94	-0.97

Table 2 Limiting Strength of Axially Loaded Columns

3.2 Eccentrically Loaded Columns

Figure 2 shows that the ultimate load for concrete columns is significantly increased by the filament wound tube. Greater axial loads and moments are achieved with tubes where the fibres are aligned at an angle between 67.5° and 80.4°. However, large lateral deflections are associated with these enhanced loads and serviceability requirements restrict the degree of enhancement achieved. Table 3 gives the axial loads at a compressive strain of 0.35%, the limiting compressive strain specified in BS8110. Figure 2 shows the failure envelope for plain concrete, based of a limiting compressive strain of 0.35% and a concrete strength of $0.67f_{cu}$. Comparison of the axial load of the columns at a compressive strain of 0.35% still shows an enhancement in the load carrying capacity.

Ref. No.	ϕ mm	α	Length mm	f_{cu} N/mm^2	e mm	Failure Load kN	δ mm	Moment kNm	Readings @ 0.35% Strain Load kN	δ mm	Moment kNm
fw4	59.86	75.5	370.0	27.9	3.0	167.4	9.67	1.62	101.5	3.83	0.39
fw5	59.86	75.5	370.0	36.2	3.0	171.6	10.94	1.88	75.8	3.50	0.27
fw6	59.86	75.5	670.2	32.3	3.0	92.3	11.80	1.09	65.9	5.50	0.36
fw9	79.85	78.1	467.8	19.7	4.0	311.7	15.13	4.72	94.0	4.60	0.43
fw10	79.85	78.1	469.6	36.4	4.0	367.4	-	-	172.2	4.29	0.74
fw12	79.85	78.1	869.7	31.2	4.0	200.5	15.85	3.18	103.7	6.22	0.64
fw13	79.85	78.1	867.9	25.6	4.0	171.0	14.72	2.52	127.8	6.06	0.77
fw17	79.89	57.8	469.6	28.2	4.0	242.8	11.54	2.80	121.6	4.52	0.55
fw18	79.89	57.8	469.1	24.6	4.0	213.0	10.72	2.28	92.3	4.48	0.41
fw20	79.89	57.8	869.0	21.5	4.0	130.9	11.82	1.55	114.7	4.11	0.70
fw21	79.89	57.8	869.7	27.2	4.0	188.2	8.44	1.59	135.5	4.13	0.56
fw25	79.89	43.4	469.1	30.7	4.0	172.3	6.55	1.13	129.5	4.43	0.57
fw26	79.89	43.4	469.9	34.4	4.0	185.1	7.20	1.33	153.0	4.81	0.74
fw29	79.89	43.4	789.9	34.3	4.0	150.0	9.35	1.40	146.2	6.35	0.92
fw33	99.97	80.4	569.7	23.4	5.0	447.3	18.77	8.40	157.9	-	-
fw34	99.97	80.4	569.9	35.2	5.0	568.4	16.98	9.65	231.2	5.11	1.18
fw36	99.97	80.4	1068.9	22.6	5.0	278.3	16.38	4.56	179.0	6.58	1.18
fw37	99.97	80.4	1070.3	32.8	5.0	311.8	15.66	4.88	226.1	6.43	1.45
fw41	100.02	71.4	569.6	29.5	5.0	392.0	16.50	6.47	228.3	5.44	1.24
fw42	100.02	71.4	569.9	31.3	5.0	398.2	14.58	5.81	223.4	5.84	1.30
fw44	100.02	71.4	1069.1	21.4	5.0	188.7	16.69	3.15	168.6	8.42	1.42
fw45	100.02	71.4	1069.8	33.2	5.0	236.8	16.46	3.90	219.3	9.05	1.98
fw49	100.03	49.9	569.9	33.7	5.0	240.2	11.49	2.76	148.3	5.74	0.85
fw50	100.03	49.9	569.9	40.1	5.0	272.8	10.67	2.91	210.6	5.50	1.16
fw52	100.03	49.9	1068.7	30.0	5.0	154.4	13.91	2.15	147.2	9.04	1.33
fw53	100.03	49.9	1069.3	29.3	5.0	176.9	12.91	2.28	171.6	9.88	1.69
fw109	300.10	86.8	1650	25.3	15.0	2530	32.45	82.10	1500	18.25	4.87
fw110	300.10	86.8	1650	36.8	15.0	3300	31.33	103.39	-	-	-
fw111	300.10	86.8	3150	39.7	15.0	2100	26.28	55.19	-	-	-
fw114	399.88	87.6	2150	29.0	20.0	5050	56.44	243.52	-	-	-
fw115	399.88	87.6	2150	40.5	20.0	5860	38.75	227.08	3680	24.89	17.99
fw116	399.88	87.6	4150	36.5	20.0	3300	26.07	86.31	-	-	-

Table 3 Experimental Results of Confined Columns

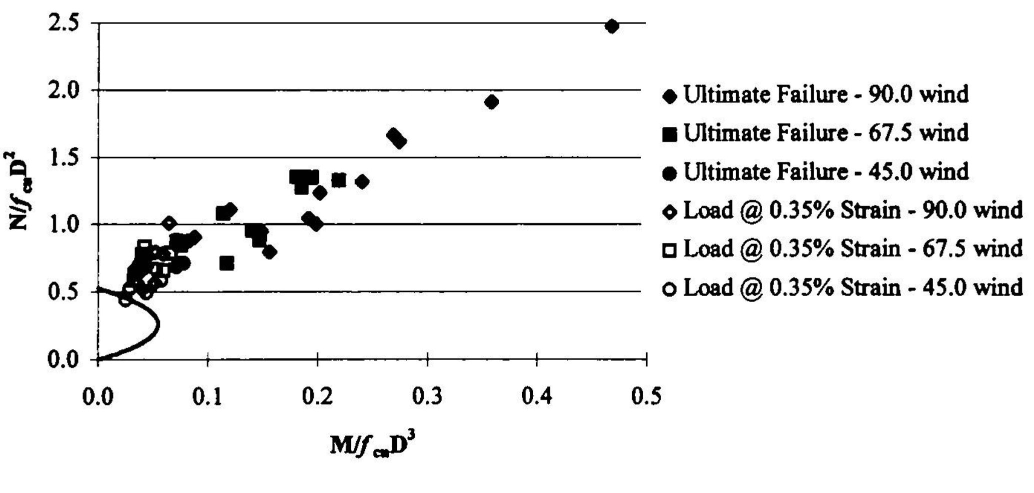

Fig 2 Interaction Diagram for Concrete Filled GFRP Columns

Consequently, the column design equation for stocky columns given in BS8110 [7] can be modified.

$$N = 0.45C_m f_{cu} A_c + 0.87 f_y A_{sc} \qquad \text{Equation 2}$$

Where C_m is an empirical coefficient that reflects the increased confidence in the strength of the concrete. Based on the preliminary results presented in this paper, the value C_m lies between 1.15 and 1.20. Limiting the concrete compressive strains to a value 0.35% also means that the existing deflection prediction equations are still valid.

4. Conclusion

Preliminary test results have shown than a significant enhancement in axial load carrying capacity can be achieved using glass fibre filament wound tubes as permanent formwork. It is not recommended that design be based on the ultimate limit state of the tube. Since, at ultimate limit state, the concrete is a highly fissured material, any loss of the confining pressure at strains exceeding 0.35% would result in immediate brittle collapse. However, designs based on existing reinforced concrete design codes can be modified to take account of the increased confidence in the strength of plain concrete, using the material confinement factor C_m value between 1.15 and 1.20 obtained statistically from these results.

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