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ANALYTICAL MODELS FOR FRP CONFINED CIRCULAR CONCRETE COLUMNS

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ABSTRACT

Jacketing a reinforced concrete column by Fibre Reinforced Polymer (FRP) wraps primarily improves column performance, not because the jacket itself carries some fraction of the axial load applied to the column, but rather because, it provides lateral confining pressure to the column. This confining pressure places the concrete in a triaxial state of stress, altering the load-deformation characteristics of concrete. But contribution of wraps in improving the load carrying capacity of columns still remains controversial and there is need to develop suitable confining models for FRP wraps.Simple analytical equations based on confinement model developed by Richart et al. with modified value of confinement effectiveness co-efficient were proposed to predict the axial load carrying capacity of FRP confined circular columns under axial loading. The proposed equations were validated through the previous experimental database available in literature. A good correlation is obtained between the proposed equations and the existing experimental results. The confined concrete strength from tests was compared with the results from the developed empirical equations and the comparisons are favorable.

Keywords: Jacketing; column; fibre reinforced polymer; confining pressure; wraps; load carrying capacity; confining models

1. INTRODUCTION

Strengthening of R.C. columns represent an engineering problem, which, like all engineering problems, involves several solutions, each having their own advantages and disadvantages and their own limits to applicability and practicality. For instance, there is a possibility to remove deficient columns and construct new columns in their place. Another solution is to place reinforcing steel and form work around an existing column and pour additional concrete. Yet another solution is to use a jacketing technique wherein the column is encased by some reinforcing material. Traditionally steel has been used to confine R.C.

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columns, but recently fiber reinforced polymer (FRP) has become a viable alternative to steel in some applications. The lateral pressure exerted by FRP will increase the compressive strength of concrete resulting in higher load carrying capacity. The lateral confinement provided by FRP will also provide additional support against buckling of the longitudinal bars. In the case of a circular cross- section, the jacket exerts a uniform confining pressure resulting in a uniform tri-axial stress field.

Amir Mirmiran, Mohsen Shahawy conducted series of uniaxial compression tests on concrete filled FRP tubes and the results were compared with the available confinement models in the literature. The study indicates that fibre composites are an effective means of confinement, as they significantly increase both strength and ductility of concrete. A comparison of test data with available confinement models indicates that while they produce acceptable results for steel-encased concrete, they overestimate the strength of FRP encased concrete. The study also shows a unique characteristic of confinement with fibre composites in that, unlike steel, FRP curtails the dilation tendency of concrete, as it reverses the direction of volumetric strains [1].

The behavior of FRP wrapped concrete cylinders with different wrapping materials and bonding dimensions has been studied by Kin-Tak Lau and Li-min Zhou using Finite Element (FEM) and analytical methods [2]. It was found that, the load carrying capacity of the wrapped concrete structure is governed by the mechanical properties such as modulus and Poisson’s ratio, of the wrapping sheet. The deflection of the wrapped concrete cylinder in the load direction decreases with increasing the length thickness and modulus of the wrapping sheet. An analytical equation was provided to estimate the shear stress distribution of an adhesive material for different wrapping geometries. The results of the equation compared well with FEM solutions.

Shahawy et al verified a confinement model which was originally developed for concrete filled glass FRP tubes by conducting axial compression tests on a total of 45 carbon-wrapped concrete stubs of two batches of normal and high strength concrete and five different number of wraps. It was concluded that, the wrap significantly enhanced the strength and ductility of concrete by curtailing its lateral dilation and the adhesive bond between concrete and the wrap would not significantly affect the confinement behaviour [3].

The analytical compressive behaviour of concrete members reinforced with FRP was examined by Campione and Miraglia. The variation in the shape of cross section was analysed. The bearing capacity and the increase in the maximum strain for members having a cross-section which was circular, square or square with round corners reinforced with FRP were determined. An analytical model is proposed to validate the confining pressure in ultimate conditions and to determine the ultimate strain corresponding to FRP failure. Analytical results show good agreement with experimental values available in literature [4].

A study on the compressive behaviour and strength of elliptical concrete specimens wrapped with CFRP has been described by Teng and Lam [5]. From the study it is found that, the axial compressive strength of FRP confined concrete in elliptical specimens is controlled by the amount of confining FRP and the major to minor axis length ratio a/b of the column section. The confining FRP becomes increasingly less effective as the section becomes more elliptical but substantial strength gains from FRP confinement can still be achieved even for strongly elliptical sections. The ultimate axial strain of the confined concrete is also shown to increase as the FRP confinement becomes larger. Based on the test results, a simple compressive strength model for FRP confined concrete in elliptical columns is proposed, in which the effect of the section shape is taken into account by a shape factor.

Hadi carried out experiments to evaluate the effectiveness of the various types of external reinforcement on the circular columns where eccentric loading was applied through especially designed loading mechanism. The experimental results clearly demonstrate that composite wrapping can enhance the structural performance of concrete columns under eccentric loading to some extent. However, the enhancement is not as significant as that of columns under concentric loading as suggested by previous studies. The test results also indicated that the carbon fibers provided the greatest amount of confinement, and had significantly better results, if the external confinement was achieved by the application of FRP in tape. The external confinement with galvanized steel straps improved the strength of the column to a certain extent. The brittle, sudden, soundless failure of the galvanized steel strap wrapped columns showed that the galvanized steel straps had very little effect on improving the ductility of the columns [6].

Teng and Lam presented a large database assembled from an extensive survey of existing studies and employed the same to assess available axial strength models for FRP confined concrete. The test database is also deployed to examine the effect of various factors on the performance of FRP confined concrete. This study shows that the confinement effectiveness of FRP, based on reported test results depends little on unconfined concrete strength, size, and length to diameter ratio of test specimens and FRP type, but depends significantly on the accuracy of the reported tensile strength of the FRP [7].

Literatures indicated that attempts have been made by different authors to improve the strength and other engineering properties like energy absorption capacity, and ductility of plain concrete circular columns strengthened with FRP. In this paper,on the basis of experimental investigations carried out on Glass Fibre Reinforced Polymer (GFRP) confined circular columns and based on the model developed by Richart et al simple analytical equations with modified value of confinement effectiveness co-efficient are proposed to predict the strength of FRP confined concrete columns with circular cross-sections under axial loading.

2. ANALYTICAL INVESTIGATION

2.1 Confined Concrete Strength

According to Richart et al for circular concrete columns confined with FRP composite wraps, the confined core concrete strength can be given as

$$f_{cc} = f_{co} + k_1 f_l \tag{1}$$

where

f_{co} = Strength of unconfined concrete

k_1 = Confinement effectiveness co-efficient.

f_l = Lateral confining pressure.

2.2 Evaluation of lateral pressure of confinement

For circular specimens, f_l is uniformly distributed and the concrete in FRP wrapped specimens is uniformly confined. For the case of concentrically loaded cylindrical columns, the lateral pressure of confinement can be evaluated by simple considerations of equilibrium of forces. As the axial stress increases, the corresponding lateral strain increases and the confining jacket develops a tensile hoop stress which is assumed to be equal to the ultimate tensile strength of FRP (f_{frp}), balanced by the radial pressure f_l, which reacts against the concrete lateral dilation as shown in Figure 1. By equilibrium considerations, the following equation can be derived:

$$f_l = \frac{2t}{D} f_{frp} = \frac{\rho_{frp} f_{frp}}{2} \tag{2}$$

where

t = Thickness of FRP jacket
D = Diameter of the concrete core
f_{frp} = Tensile strength of FRP in hoop direction
ρ_{frp} = FRP volumetric ratio $= \frac{4t}{D}$

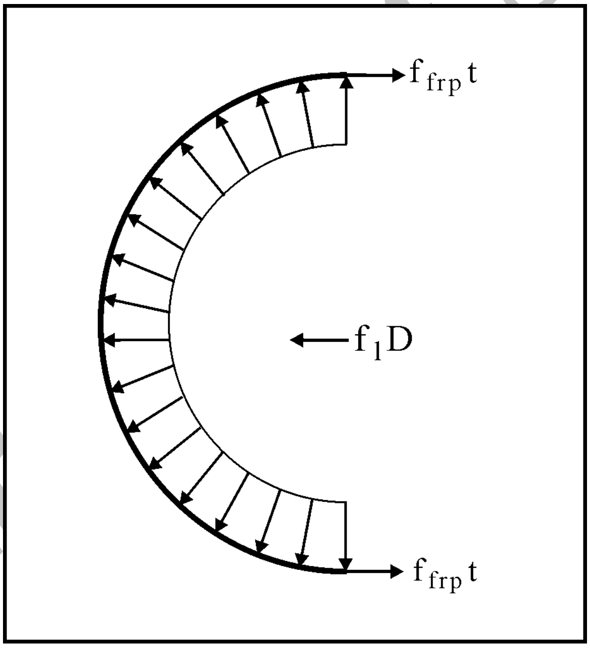

Figure 1. Confinement pressure due to FRP

2.3 Confinement Ratio (CR) and Stengthening Ratio (SR)

The confinement ratio of FRP confined concrete is defined as ratio of the maximum confining pressure to the unconfined concrete strength. It is given by

$$CR = \frac{f_l}{f_{co}} \tag{3}$$

Strengthening ratio or confinement effectiveness is defined as the ratio between the strength of confined concrete to that of unconfined concrete, that measures how effectively the concrete is confined in a given cross section. It is given by

$$SR = \frac{f_{cc}}{f_{co}} \tag{4}$$

2.4 Parameters for confinement effect

The main parameters that are likely to influence the confinement effect are the volumetric fibre reinforcement ratio, yield strength of fibre reinforcement, core concrete shape and the strength of unconfined concrete. The effect of confinement on these parameters was determined based on the test results. The test results of GFRP confined plain concrete cylinder specimens are given in Table 1. It can be seen that the peak stress of the confined concrete depends on the value of the lateral confinement pressure f_l. Figure 2 shows the relation between confinement ratio and the ratio of the peak stress to the strength of the unconfined concrete for the plain concrete circular specimens of the test series together with the respective linear regression.

The peak strength f_{cc} of the confined specimens was normalized by the strength of unconfined concrete f_{co}. It can be seen that, the normalized confined compressive strength, approximately, increase linearly with the increase of the normalized confining lateral pressure. Therefore the relationship may be approximated by a linear function, with the slope depending on the cross-sectional shape. Making use of the experimental results, from the regression analysis, the relation between confinement ratio and strengthening ratio is written as

$$\frac{f_{cc}}{f_{co}} = 1 + 3.35\frac{f_l}{f_{co}} \tag{5}$$

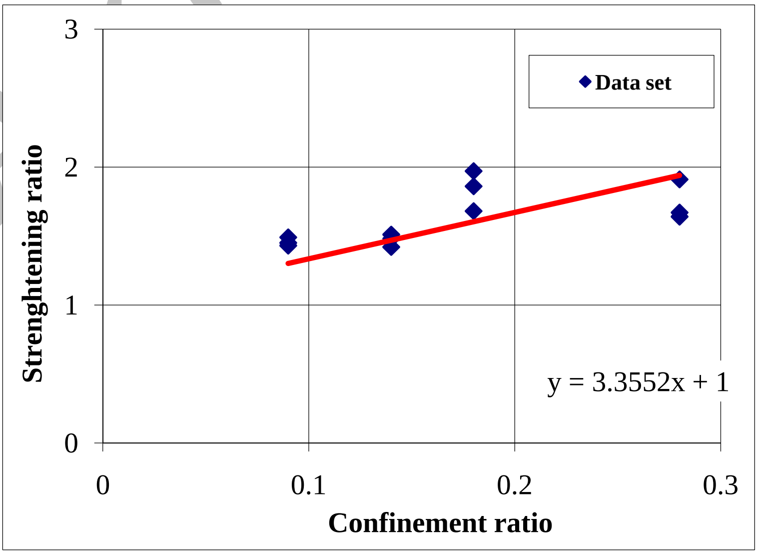

Figure 2. Strengthening ratio vs confinement ratio-Plain concrete cylinders

Table 1: Test results of GFRP confined plain concrete circular specimens

S. No.	***D* (mm)**	***L* (mm)**	**Fibre type**	**f_{co} (N/mm^2)**	***t* (mm)**	**f_{frp} (N/mm^2)**	**E_{frp} (N/mm^2)**	**f_l (N/mm^2)**	**f_l / f_{co}**	**f_{cc} (N/mm^2)**	**f_{cc} / f_{co}**
1	150	300	CSM	24.13	1.1	150	11000	2.2	0.09	35.10	1.45
2	150	300	CSM	24.13	1.1	150	11000	2.2	0.09	36.01	1.49
3	150	300	CSM	24.13	1.1	150	11000	2.2	0.09	34.57	1.43
4	150	300	CSM	24.13	2.2	150	11000	4.4	0.18	47.44	1.97
5	150	300	CSM	24.13	2.2	150	11000	4.4	0.18	40.57	1.68
6	150	300	CSM	24.13	2.2	150	11000	4.4	0.18	44.88	1.86
7	150	300	WRM	24.13	1.0	250	19500	3.34	0.14	34.34	1.42
8	150	300	WRM	24.13	1.0	250	19500	3.34	0.14	35.60	1.48
9	150	300	WRM	24.13	1.0	250	19500	3.34	0.14	36.47	1.51
10	150	300	WRM	24.13	2.0	250	19500	6.68	0.28	39.63	1.64
11	150	300	WRM	24.13	2.0	250	19500	6.68	0.28	40.25	1.67
12	150	300	WRM	24.13	2.0	250	19500	6.68	0.28	45.98	1.91

2.5 Comparison of confined strength

The strength of the FRP confined concrete predicted from the proposed analytical Eq. (5) was compared with the experimental results as shown in Table 2. It was found that a good correlation was obtained between the experimental results and those got from the equation . It can be seen that the proposed equation predicts the behaviour of confined concrete with most accuracy. The same model can also be used to find the ultimate strength of concrete confined with all types of fibre sheets namely carbon, aramid etc.

Table 2: Comparison of experimental and analytical results

S. No	**Spec. ID**	**f_{cc} (N/mm^2)**		**$f_{cc,cal} / f_{cc,exp}$**
		Experiment	**From Eq. (5)**	
1	C_1	35.10	31.4	0.89
2	C_1	36.01	31.4	0.87
3	C_1	34.57	31.4	0.91
4	C_2	47.44	38.7	0.82
5	C_2	40.57	38.7	0.95
6	C_2	44.88	38.7	0.86
7	W_1	34.34	35.4	1.03
8	W_1	35.60	35.4	0.99
9	W_1	36.47	35.4	0.97
10	W_2	39.63	46.7	1.18
11	W_2	40.25	46.7	1.16
12	W_2	45.98	46.7	1.01

2.6 Validation of proposed equation with existing experimental data base in literature

A large number of tests have been reported in the literature on the axial compressive strength of circular concrete specimens confined by FRP.A database containing test results was built from a survey of existing studies [7] and the results are presented in Table 3.

Only test results on circular specimens without steel reinforcement were considered. These data are all for fully confined plain concrete circular specimens with unconfined concrete strengths not greater than 60MPa.All these specimens failed by FRP rupture. Carbon Fibre Reinforced Plastics (CFRP) and Glass Fibre Reinforced Plastics (GFRP) have been used in these tests. The confinement ratio varies from 0.03 to 0.84.

The experimental results of confined concrete strength reported in the existing database found in the literature were compared with those of the confined strength computed from Eq. (5). The comparison is shown in Table 3 and is found to be favorable. Hence, equation (5) can be satisfactorily applied to determine the axial compressive strength of FRP confined concrete circular specimens.

Table 3: Validation of proposed equation with existing experimental results

S. No.	D (mm)	L (mm)	$\frac{L}{D}$	Type of FRP	t (mm)	f_{frp} (N/mm^2)	E_{frp} (N/mm^2)	f_{co} (N/mm^2)	$\frac{f_l}{f_{co}}$	f_{cc} (N/mm^2) Experiment	f_{cc} (N/mm^2) From Eq. (5)	$f_{cc,cal}/f_{cc,exp}$
1	152	305	2.0	CFRP	0.31	755	73300	38.6	0.08	47.2	48.9	1.04
2	152	305	2.0	CFRP	0.61	1047	70600	38.6	0.22	60.6	67.0	1.11
3	152	305	2.0	CFRP	0.61	1047	70600	38.6	0.22	61.9	67.0	1.08
4	152	305	2.0	CFRP	0.92	1105	77500	38.6	0.34	80.9	82.6	1.02
5	152	305	2.0	CFRP	0.92	1105	77500	38.6	0.34	76.4	82.6	1.08
6	152	305	2.0	CFRP	0.92	1105	77500	38.6	0.34	75.8	82.6	1.09
7	152	305	2.0	CFRP	0.92	822	54000	38.6	0.26	68.3	72.2	1.06
8	152	305	2.0	CFRP	0.92	822	54000	38.6	0.26	67.3	72.2	1.07
9	152	305	2.0	CFRP	1.22	388	27700	38.6	0.16	52.6	59.3	1.13
10	100	200	2.0	CFRP	0.42	1285	576600	30.2	0.36	63.3	66.6	1.05
11	100	200	2.0	CFRP	0.14	1579	628600	30.2	0.15	41.7	45.3	1.09
12	152	610	4.0	GFRP	1.0	383	21600	26.2	0.19	38.4	42.8	1.11
13	152	610	4.0	GFRP	1.0	383	21600	26.2	0.38	52.5	59.5	1.13
14	152	610	4.0	CFRP	1.0	580	38100	26.2	0.29	50.6	51.7	1.02
15	150	300	2.0	CFRP	0.12	2600	200000	34.9	0.12	44.3	48.9	1.10
16	150	300	2.0	CFRP	0.12	2600	200000	34.9	0.12	42.2	48.9	1.16
17	150	300	2.0	CFRP	0.24	1100	420000	34.9	0.10	41.3	46.5	1.13
18	150	300	2.0	CFRP	0.24	1100	420000	34.9	0.10	40.7	46.5	1.14
19	153	305	2.0	GFRP	1.45	524	37233	29.6	0.34	67.1	63.3	0.94
20	153	305	2.0	GFRP	1.45	524	37233	29.6	0.34	60.2	63.3	1.05
21	153	305	2.0	GFRP	2.21	579	40336	29.6	0.57	93.0	86.1	0.93
22	153	305	2.0	GFRP	2.97	641	40749	29.6	0.84	114.7	112.9	0.98
23	153	305	2.0	GFRP	1.45	524	37233	32.0	0.31	60.8	65.2	1.07
24	51	102	2.0	CFRP	0.09	3500	235000	41.0	0.30	86.0	82.2	0.96
25	51	102	2.0	CFRP	0.18	3500	235000	41.0	0.60	117.0	123.4	1.05
26	152	305	2.0	CFRP	0.3	380	25000	43.7	0.03	48.4	48.1	0.99
27	150	300	2.0	GFRP	0.3	583	52000	36.3	0.06	46.0	43.6	0.95
28	150	300	2.0	GFRP	0.6	583	52000	36.3	0.13	55.8	52.1	0.93
29	150	300	2.0	GFRP	0.6	583	52000	36.3	0.13	56.4	52.1	0.92
30	150	300	2.0	GFRP	2.4	583	52000	36.3	0.51	104.9	98.3	0.94
31	150	300	2.0	GFRP	2.4	583	52000	36.3	0.51	106.9	98.3	0.92

S. No.	***D* (mm)**	***L* (mm)**	$\frac{L}{D}$	**Type of FRP**	***t* (mm)**	f_{frp} **(N/mm²)**	E_{frp} **(N/mm²)**	f_{co} **(N/mm²)**	$\frac{f_l}{f_{co}}$	f_{cc} **(N/mm²)**		$f_{cc,cal}/f_{cc,exp}$
										Experiment	**From Eq. (5)**	
32	150	300	2.0	GFRP	2.4	583	52000	36.3	0.51	107.9	98.3	0.91
33	152	305	2.0	CFRP	0.16	1481	140000	46.0	0.07	53.0	56.8	1.07
34	150	300	2.0	CFRP	0.11	3481	230500	45.2	0.11	59.4	61.9	1.04
35	150	300	2.0	CFRP	0.22	3481	230500	45.2	0.23	79.4	80.0	1.01
36	150	300	2.0	CFRP	0.11	3481	230500	31.2	0.16	52.4	47.9	0.91
37	150	300	2.0	CFRP	0.11	3481	230500	31.2	0.33	67.4	65.7	0.97
38	100	200	2.0	CFRP	0.11	3481	230500	51.9	0.15	75.2	77.9	1.04
39	100	200	2.0	CFRP	0.22	3481	230500	51.9	0.30	104.6	104.1	0.99
40	100	200	2.0	CFRP	0.22	3481	230500	33.7	0.45	88.0	84.5	0.96
41	100	200	2.0	CFRP	0.33	3481	230500	33.7	0.68	109.9	110.5	1.01
42	76	305	4.0	GFRP	0.24	1518	69000	31.8	0.30	63.2	63.8	1.01
43	76	305	4.0	CFRP	0.22	3485	228000	31.8	0.63	98.7	98.9	1.00
44	150	300	2.0	CFRP	0.11	3481	230500	23.6	0.22	36.5	40.9	1.12
45	100	200	2.0	CFRP	0.11	3481	230500	26.3	0.29	50.7	51.8	1.02
46	100	200	2.0	CFRP	0.22	3481	230500	26.3	0.58	70.9	77.4	1.09
47	191	788	4.1	CFRP	0.22	3483	230535	27.1	0.30	53.9	54.3	1.01
48	76	305	4.0	GFRP	0.24	1518	72600	31.0	0.30	60.8	62.1	1.02
49	76	305	4.0	CFRP	0.22	3485	230500	31.0	0.65	95.0	98.5	1.04
50	152	435	2.9	GFRP	0.8	450	32000	35.0	0.13	52.8	50.2	0.95
51	152	435	2.9	GFRP	1.6	505	34000	35.0	0.3	66.0	70.1	1.06
52	152	435	2.9	CFRP	0.11	3300	367000	35.0	0.14	55.0	51.4	0.93
53	152	435	2.9	CFRP	0.23	3550	390000	35.0	0.31	68.0	71.3	1.05

3. CONCLUSIONS

Simple analytical equations based on confinement model developed by Richart et al. were proposed to predict the axial load carrying capacity of FRP confined circular columns under axial loading. The proposed equations were validated through the previous experimental database available in literature. A good correlation is obtained between the proposed equations and the existing experimental results. The confined concrete strength from tests was compared with the results from the developed empirical equations and the comparisons are favorable.

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