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Predictive model for confinement pressure of partially FRP confined concrete columns

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Abstract

Nowadays, application of FRP wraps is a common approach for strengthening columns. Various relationships have been proposed to determine the compressive strength of FRP confined concrete taking advantage of the confinement pressure. It should be noted that in some cases partial confinement is used due to some reasons. Therefore, the FRP confinement pressure differs with the case of continues confinement because of non-uniform distribution of confinement pressure. Therefore, modified relations for confinement pressure are required. Accordingly, in the present study, the authors try to propose a new and more accurate model for the confinement pressure of partially confined circular and square columns using experimental results and the Multi-Expression Programming (MEP).

Keywords: Confinement pressure, FRP, Partial confinement, Compressive strength, Circular and Square section.

1. INTRODUCTION

The structural component may require strengthening during their service life due to different reasons such as eccentric loading, seismic forces and structural extensions. A common strengthening method for confinement of concrete columns is using appropriate materials. Nowadays, application of fiber reinforced polymers (FRPs) for confining reinforced concrete columns is a common practice. Previous studies by Tamuzs et al., Wang et al., Faustino et al. and Nistico on the CFRP confined circular and rectangular concrete columns proved that confinement increases load carrying capacity and ductility of the columns [1-4]. Lingola et al. utilized the Mohr-Coulomb strength criteria to determine increase in the compressive strength of FRP confined concrete columns [5]. Krevaikas and Triantafillou are the first researchers who investigated effect of CFRP and GFRP wraps on performance of masonry columns [6]. Their findings proved that FRP confinement increases strength and ultimate axial deformation of the columns and this effect is more evident in circular sections. In rectangular cross sections, due to nonuniform distribution of confinement pressure, strength improvement is less than circular sections. Therefore, rounding corners of rectangular and square sections is a common practice to prevent large stress concentration and accordingly improve confinement action [7-10]. Until now, various studies are performed on proposing predictive relation for confined strength of circular and non-circular columns. The early models were developed based on modification of the relations of confined concrete with steel casing [11-12]. However, due to linear stress-strain behavior of FRP and lack of yield point, the passive confining pressure due to FRP wraps is different from that of steel casings. As mentioned, there are many available models for FRP confined concrete columns. These relations can be categorized in two distinct group of design oriented and analytical oriented [13]. The first group consists of the models derived by performing regression on a set of experimentally derived results, while the second category of models are derived from incremental analysis of stress-strain curves [3, 14-22]. Due to simplicity of application, the design-oriented relations are used widely for practical purposes, however they might be less accurate than the analysis-oriented ones.

2. CONFINEMENT MODELS

It should be noted that in most of the existing models, the increase in the strength of the column is a function of the provided confinement pressure by FRP wraps which is derive from the following relation:

$$f_l = \frac{\rho_{frp} f_{frp}}{2} = \frac{\pi d t_{frp} f_{frp}}{2\frac{\pi d^2}{4}} = \frac{2 t_{frp} f_{frp}}{d} \quad (1)$$

In this equation, f_l is the confinement pressure f_{frp}, t_{frp} and ρ_{frp} are tensile strength, total thickness and volume ratio of FRP wraps, respectively. d indicates diameter of the column. This equation is valid for the confinement pressure of continuous wraps. In some cases, partial confinement in the form of separate strips are used for confining columns. In this circumstance, the distribution of confinement pressure in the height of column is not uniform. Fig. 1 demonstrate schematic view of partially confined circular and square sections.

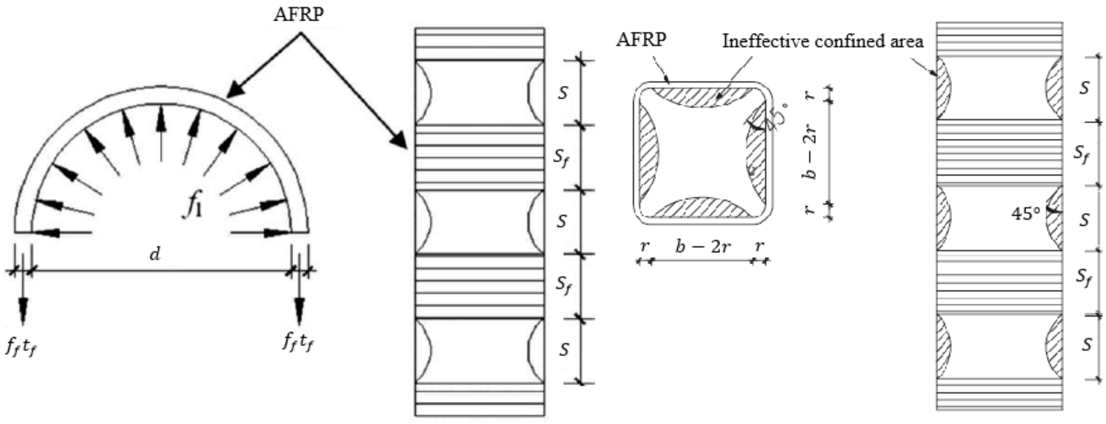

Figure 1. Mechanisms of partial confinement due to AFRP sheets

Until now, limited studies are performed regarding the effective confinement pressure in the partially confined circular and square concrete cores. In 2009, Wu et al. and Wang et al. proposed design-oriented models to predict effective pressure due to partial confinement [23-24]:

$$f_{lm} = k_e \frac{s_f}{s_f + s} f_l \quad \text{for circular columns} \quad (2)$$

$$k_e = \frac{\left[d - (\frac{S}{2})\right]^2}{d^2} \quad (3)$$

$$f_{lm} = k_e \frac{s_f + (1-\frac{s}{2b})^2 s}{s_f + s} \times \frac{s_f}{s_f + s} f_l \quad \text{for square columns} \quad (4)$$

$$k_e = \frac{\left[b^2 - (4r^2 - \pi r^2)\right] - \frac{2}{3}(b - 2r^2)}{b^2 - (4r^2 - \pi r^2)} \quad (5)$$

In these equations, k_e is called the effective confinement pressure. s and s_f are the clear space between the wraps and width of FRP wraps, respectively. b and r denote side length and radius of curvature of square cross section, respectively. This modified confinement pressure can be used in conjunction with any of the existing strength model of FRP confined concrete columns to predict maximum strength of partially confined columns. The goal of the present study is to propose new modified relations for partial confinement pressure of circular sections using design-oriented approach. For this purpose, a set of experimental results on partially confined columns is collected from the previous studies. The collected database is reported in Table 1. Since in many of the collected experimental results, width of the partial FRP wraps is not reported, it is assumed that the only influential parameters are column diameter and clear spacing between FRP wraps. On the other hand, as mentioned previously, the modified confinement pressure should be replaced in a strength model predict the maximum stress of confined concrete. In this study, the following model which is proposed by Arabshahi et al. will be used [25]:

$$\frac{f_{cc}}{f_{co}} = 1 + \frac{39 f_l}{f_{co}\,(\ln(f_{co}))^2} \tag{6}$$

Now, by substituting the experimental outcomes in this model, the required modified confinement pressure for each specimen is computed. In the next step, the calculated values of confinement pressure are considered as the dependent parameters which is a function of column diameter and clear spacing between FRP wraps. These datasets are used as input parameters in the Multi-Expression Programming (MEP). MEP is a variant of genetic programming that attracted more attentions in recent years. One of the main advantages of MEP is its ability to encode multiple solutions in the same chromosomes. This provides the opportunity to search wider zones of the search space. This algorithm commences by production of a random population. Then, pairs of parents are selected based on a binary tournament procedure and the next generation is produced by recombining the parents with a fixed crossover probability, or mutating the offspring and replacing the worst individual in the current population with the best of them. This process continues to produce the best expression within specified number of generations or until reaching a termination condition.
The following relation for modified confinement pressure is derived from MEP calculations:

$$f_{lm} = \frac{5d + S}{5d + S\,(5\mathrm{d} - S^2)} \tag{7}$$

Table 1. Database of available experimental results for confined circular columns Partially

No	References	type	Fco (MPa)	eco (%)	D (mm)	H (mm)	Ffrp (MPa)	Efrp (MPa)	t frp (mm)	f cc (MPa)	S (mm)	S_f (mm)
1		Glass	38.99	0.22	101.6	203.2	2070	48300	0.88	115.3	0	N.r
2		Glass	50.51	0.22	101.6	203.2	2070	48300	0.88	135.1	0	N.r
3		Glass	64.24	0.22	101.6	203.2	2070	48300	0.88	145.6	0	N.r
4		Glass	38.99	0.24	101.6	203.2	2070	48300	0.88	74.11	3.2	N.r
5	Ahmad et al. [26]	Glass	50.51	0.24	101.6	203.2	2070	48300	0.88	80.73	3.2	N.r
6		Glass	64.24	0.24	101.6	203.2	2070	48300	0.88	83.5	3.2	N.r
7		Glass	38.99	0.27	101.6	203.2	2070	48300	0.88	51.61	6.4	N.r
8		Glass	50.51	0.27	101.6	203.2	2070	48300	0.88	68.66	6.4	N.r
9		Glass	64.24	0.27	101.6	203.2	2070	48300	0.88	71.1	6.4	N.r
10		Aramid	35.6	N.r	150	300	1150	62200	3.8	192.2	0	N.r
11		Aramid	35.6	N.r	150	300	1150	62200	3.8	186.4	0	N.r
12		Aramid	35.6	N.r	150	300	1150	62200	4.3	243.86	0	N.r
13		Aramid	35.6	N.r	150	300	1150	62200	4.3	243.92	0	N.r
14		E glass	36.3	N.r	150	300	583	52000	0.3	46	0	N.r
15	Nanni& Bradford [27]	E glass	36.3	N.r	150	300	583	52000	0.3	41.2	0	N.r
16		E glass	36.3	N.r	150	300	583	52000	0.6	60.5	0	N.r
17		E glass	36.3	N.r	150	300	583	52000	0.6	59.2	0	N.r
18		E glass	36.3	N.r	150	300	583	52000	0.6	59.8	0	N.r
19		E glass	36.3	N.r	150	300	583	52000	0.6	60.2	0	N.r
20		E glass	36.3	N.r	150	300	583	52000	0.6	69	0	N.r

21		E glass	36.3	N.r	150	300	583	52000	0.6	55.8	0	N.r
22		E glass	36.3	N.r	150	300	583	52000	0.6	56.4	0	N.r
23		E glass	36.3	N.r	150	300	583	52000	1.2	84.9	0	N.r
24		E glass	36.3	N.r	150	300	283	52000	1.2	84.3	0	N.r
25		E glass	36.3	N.r	150	300	583	52000	1.2	79.6	0	N.r
26		E glass	36.3	N.r	150	300	583	52000	2.4	106.9	0	N.r
27		E glass	36.3	N.r	150	300	583	52000	2.4	104.9	0	N.r
28		E glass	36.3	N.r	150	300	583	52000	2.4	107.9	0	N.r
29		Aramid	35.6	N.r	150	300	1150	62200	0.37	40.24	50	N.r
30		Aramid	36.6	N.r	150	300	1150	62200	0.37	39.02	50	N.r
31		Aramid	37.6	N.r	150	300	1150	62200	0.75	45.12	25	N.r
32		Aramid	38.6	N.r	150	300	1150	62200	0.75	46.24	25	N.r
33		Aramid	39.6	N.r	150	300	1150	62200	0.77	40.24	50	N.r
34		Aramid	40.6	N.r	150	300	1150	62200	0.77	42.68	50	N.r
35		Aramid	41.6	N.r	150	300	1150	62200	1.54	70.73	25	N.r
36		Aramid	42.6	N.r	150	300	1150	62200	1.54	70.73	25	N.r
37		Aramid	43.6	N.r	150	300	1150	62200	1.03	43.9	50	N.r
38		Aramid	44.6	N.r	150	300	1150	62200	1.03	48.79	50	N.r
39		Aramid	45.6	N.r	150	300	1150	62200	2.05	70.73	25	N.r
40		Aramid	46.6	N.r	150	300	1150	62200	2.05	118.87	25	N.r
41	Vasumati et al. [28]	carbon	25	N.r	125	800	4300	230000	0.131	29.04	20	50
42		carbon	25	N.r	125	800	4300	230000	0.262	34.37	20	50
43		carbon	25	N.r	125	800	4300	230000	0.393	43.62	20	50
44		carbon	25	N.r	125	800	4300	230000	0.131	28.88	30	50
45		carbon	25	N.r	125	800	4300	230000	0.262	32.65	30	50
46		carbon	25	N.r	125	800	4300	230000	0.393	40.19	30	50
47	wu et al [29]	Aramid	46.43	0.26	100	300	2060	118000	0.286	47.37	50	50
48		Aramid	46.43	0.26	100	300	2060	118000	0.572	60.61	50	50
49		Aramid	46.43	0.26	100	300	2060	118000	0.858	74.8	50	50
50		Aramid	78.5	0.45	100	300	2060	118000	0.286	83.81	50	50
51		Aramid	78.5	0.45	100	300	2060	118000	0.572	93.85	50	50
52		Aramid	78.5	0.45	100	300	2060	118000	0.858	101.61	50	50
53		Aramid	101.18	0.46	100	300	2060	118000	0.286	101.2	50	50
54		Aramid	101.18	0.46	100	300	2060	118000	0.572	116.13	50	50
55		Aramid	101.18	0.46	100	300	2060	118000	0.858	111.25	50	50

N.r : Not reported

3. EVALUATIONS AND RESULTS

To evaluate accuracy of the proposed relation, using the strength model suggested by Arabshahi et al. (Eq. 6), the ultimate strength of the partially confined experimental results in Table 1 are calculated. Four different error measures which are introduced by the succeeding equations are use in this study:

- Root mean square error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{X_{the} - X_{exp}}{X_{exp}}\right)^2}{n}} \quad (8)$$

- Mean absolute error:

$$MAE = \frac{\sum_{i=1}^{n}\left|\frac{X_{the} - X_{exp}}{X_{exp}}\right|}{n} \quad (9)$$

- Integral absolute error:

$$IAE = \frac{\left(\sum_{i=1}^{n}\sqrt{\left|(X_{the} - X_{exp})^2\right|}\right)}{\sum_{i=1}^{n} X_{exp}} \quad (10)$$

- Coefficient of determination:

$$R^2 = \left[\frac{\left(\sum_{i=1}^{n}(X_{the} - \bar{X}_{the})(X_{exp} - \bar{X}_{exp})\right)}{\left(\sqrt{\sum_{i=1}^{n}(X_{the} - \bar{X}_{the})^2 \sum_{i=1}^{n}(X_{exp} - \bar{X}_{exp})^2}\right)}\right]^2 \quad (11)$$

here, X_{the} and X_{exp} are the theoretical and experimental values, respectively, and n stands for the number of specimens. $\bar{X}_{the}$ and $\bar{X}_{exp}$ are the mean values of the theoretical and experimental estimations, respectively. The index R^2 varies from 0 to 1, and higher value indicates better fit of a model. On the other hand, for the error measures introduced by Eq. (8) to (10), a lower value indicates higher accuracy and on the limit state, a completely exact model would have error measures equal to zero.

The attained error measure for the proposed relation is compared with the relation suggested by Wu et al. (Eq. 2) in Figs. 2 and 3.

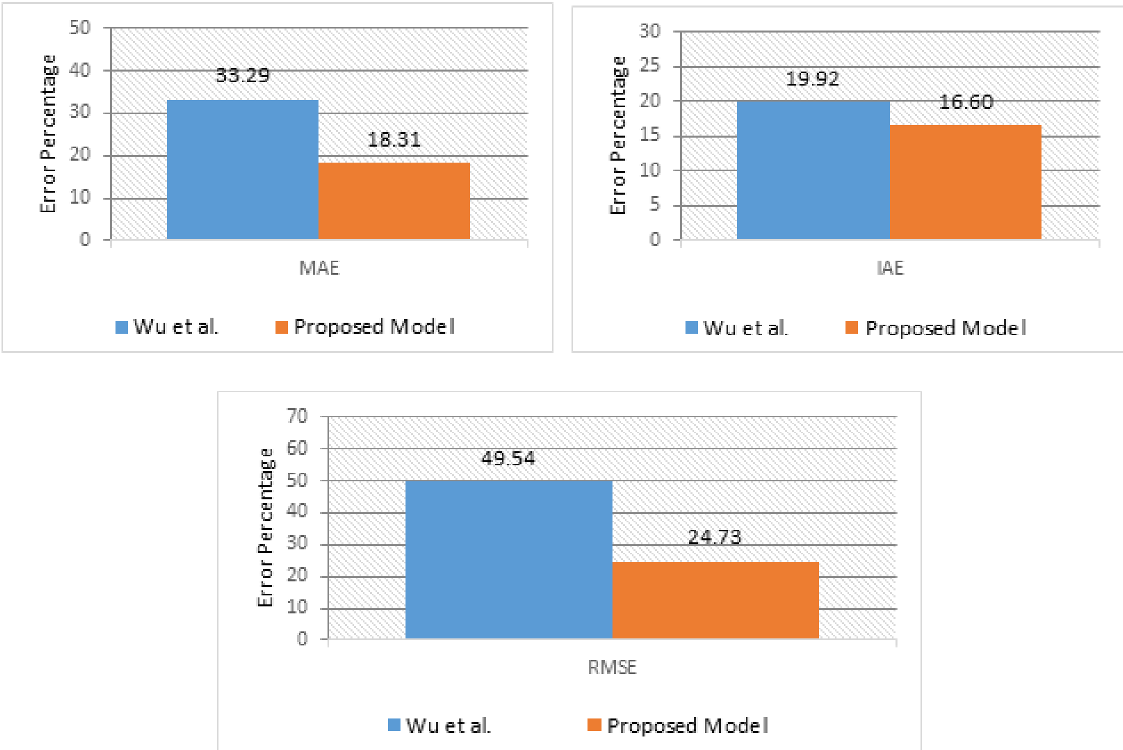

Fig 2. Different error criteria for partial confined stress models of circular sections

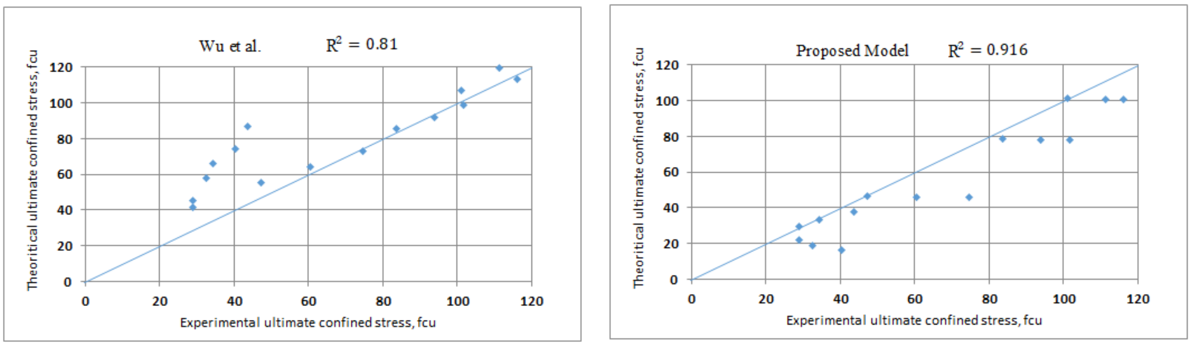

Fig 3. Performance of strength models for circle sections based on the validated experimental data

These figures show that the proposed relation results in more accurate estimations that the model proposed by Wu et al. In addition, according to the Fig. 3, it is concluded that utilization of the proposed model for practical purposes provides more conservative and safer results than the Wu et al. model, because as it is evident, application of their model leads to overestimation of the partially confined columns.

4. CONCLUSION

Due to increasing application of FRPs for strengthening and retrofitting of concrete components and especially columns, applicable relations for predicting strength of confined concrete elements is necessary. Various predicting models are proposed by researchers which are mostly applicable for continuously confined columns. Accordingly, in the case of partially confined columns, utilization of mentioned relations provides inaccurate estimations of the ultimate strength of column which are more than actual strength. Therefore, modification of existing strength models for the mentioned condition is required. Accordingly, in the present study, using a database of experimental results on partially confined columns and an evolutionary algorithm called MEP, a new design-oriented model for confinement pressure of partially confined circular concrete columns is proposed. The numerical evaluation proved that application of the suggested relation in strength models of FRP confined concrete columns provides more accurate than the previously proposed model by Wu et al. In addition to higher accuracy, the suggested relation also results in more conservative estimations which are desirable from safety standpoint in design applications.

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