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Ultimate stress and strain models for AFRP confined concrete columns with inclined fiber orientation

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Abstract

Various stress and strain models are proposed for FRP confined concrete columns. Almost all of these relations are developed by assuming fiber angles perpendicular to the column axis. Therefore, application of these relation to predict ultimate confined stress and strain of columns confined with FRPs having incline fibers results in inaccurate estimations. Accordingly, in this paper, modification factors are proposed to make the available stress and strain models applicable for the FRP confinement with inclined fiber orientation. For this purpose, a database of experimental tests on such columns are collected from the previous studies. The part of the collected database is used to calibrate some of the best performing confined stress and strain models utilizing nonlinear regression techniques and an evolutionary optimization algorithm called Multi-Expression Programming (MEP). The attained results indicate good accuracy of the suggested relations in estimating ultimate stress and strain of FRP confined concrete columns with inclined fiber angle.

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

1. INTRODUCTION

Since application of fiber reinforced polymers (FRPs) for strengthening and rehabilitation of concrete structural components and especially columns, various researchers tried to propose predictive models for ultimate stress and strain of confined concrete experimentally and analytically [1-6]. These models can be classified in two general categories, namely Analysis-oriented and Design-oriented [1]. The first group is established by performing incremental analysis to achieve stress–strain curve [2,3,7]. On the other hand, Design- oriented methods are proposed by adjusting predefined mathematical formulae based on numerical regression using databases of existing experimental results [8-11]. The second group is preferred because of higher effortlessness and comfort application, while the consistency of the first group with mechanical behavior of confined concrete is more than second group. However, most of the existing models for FRP confined concrete columns are proposed assuming fiber orientation perpendicular to the column axis. In addition, many of the previous models are developed using experimental results derived mostly from GFRP or CFRP confined concrete columns. However, nowadays other types of fibers such as Aramid are also used in constructional applications Due to the proper behavior of aramid fibers against different loads, especially seismic loads, the use of these fibers is nowadays considered in cases where concrete components are subject to seismic loads and require high energy absorption. As depicted in Fig. 1, the Aramid fibers have the average properties of Carbon and Glass fibers. Accordingly, in recent years various studies are performed regarding properties and applications of Aramid fibers [12-19].

Since the existing models for ultimate stress and strain of confined concrete are proposed for common conditions, correction factors are proposed by investigators to make the available models for different conditions and incorporate effects such as size effect, various types of FRP attachment and etc. [20-22]. One of the parameters that considerably affect ultimate strength and strain of FR confined concrete column is orientation of fibers. Therefore, it is necessary to propose correction factors for stress and strain model that modify prediction of relations which are proposed for the case of fibers perpendicular to the column axis. Based on this necessity, such corrective relation is suggested to modify prediction of one of the best performing models for AFRP confined circular columns.

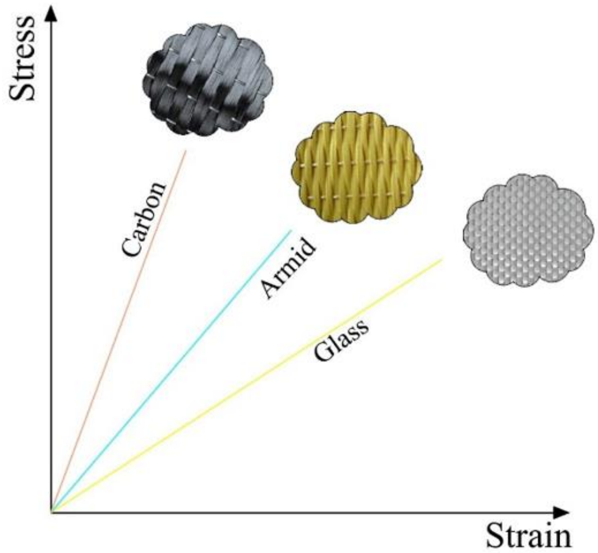

Fig 1. Schematic stress-strain diagram of different types of FRP

2. The utilized stress and strain models

Despite the large number of existing relations for ultimate strength and strain of FRP confined concrete column, in recent years various researchers attempted to propose new and more accurate relations for specific types of FRP and especially AFRP [9, 13, 14, 18, 22]. In this study the latest suggested models which is also among the most accurate ones for AFRP confined circular concrete columns will be used. These relations which are proposed by Arabshahi et al. [5] are as follows:

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

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = \frac{0.21 f_l^{\,0.68}}{\varepsilon_{co}\,(f_{co} - \ln(\varepsilon_{co}))} \tag{2}$$

In these relations, f_{cc}, f_{co}, ε_{cc} and ε_{co} are confined and unconfined concrete strengths and strains, respectively. In addition, f_l indicate confinement pressure provided by AFRP wraps:

$$f_l = \frac{\rho_{frp} f_{frp}}{2} = \frac{\pi d t_{frp} f_{frp}}{2\frac{\pi d^2}{4}} = \frac{2 t_{frp} f_{frp}}{d} \tag{3}$$

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

3. Derivation of modification relations

To propose correction factors, first a database of experimental results on circular concrete column with AFRP wraps with inclined fiber angles is collected from the previous researches. The collected results are listed in Table 1. It should be noted that the reported angles in the table are computed from the longitudinal axis of the column.

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.
Using the database as input of the Multi-Expression Programming, the following correction factor is computed for stress and strain models, respectively:

$$C_{FAstress} = Sin(\alpha) - (2Sin^{3}(\alpha)Cos(\alpha) + 0.5)(\mathrm{Sin}^{4}(\alpha)Cos(\alpha)) \tag{4}$$

$$C_{FAstrain} = 1 - Sin(\alpha)Cos(\alpha) - Cos(\alpha) + Sin(\alpha)Cos^{2}(\alpha)) \tag{5}$$

In these relations, α is the angle of fibers with column axis.

Table 1- Collected experimental database

No	References	Concrete properties		Specimen Dimensions		AFRP properties			Experimental outcome		
		f_{cc} (MPa)	ε_{co} (%)	d (mm)	L (mm)	f_f (MPa)	E_f (GPa)	t_f (mm)	f_{cc} (MPa)	ε_{cu} (%)	Additional info
1	Vincent and Ozbakkaloglu 2013 [23]	70.00	0.28	100	200	2930	99.0	0.600	70.50	0.63	IFA(45°)
2		79.50	0.30	100	200	2930	99.0	0.600	80.90	0.37	IFA(45°)
3		85.50	0.31	100	200	2930	99.0	0.600	87.60	0.40	IFA(45°)
4		80.50	0.30	100	200	2930	99.0	0.600	82.40	1.40	IFA(60°)
5		78.00	0.30	100	200	2930	99.0	0.600	79.10	1.48	IFA(60°)
6		74.00	0.29	100	200	2930	99.0	0.600	74.50	0.71	IFA(60°)
7		83.00	0.31	100	200	2930	99.0	0.600	108.30	1.25	IFA(75°)
8		83.00	0.31	100	200	2930	99.0	0.600	111.60	1.42	IFA(75°)
9		85.90	0.31	100	200	2930	99.0	0.600	117.30	1.48	IFA(75°)
10		85.90	0.31	100	200	2930	99.0	0.600	176.20	2.89	IFA(88°)
11		83.00	0.31	100	200	2930	99.0	0.600	154.90	2.53	IFA(88°)
12		85.90	0.31	100	200	2930	99.0	0.600	176.60	2.89	IFA(88°)

*** IFA: Inclined Fiber Angle**

3. Evaluation of the results

To evaluate correlation of the predicted values by the suggested factors with the ratio of experimental ultimate stress and strains to the values derived by models of Eq. (1) and (2), the following relation is used:

$$R^{2} = \left[\frac{\left(\sum_{i=1}^{n}(X_{the} - \bar{X}_{the})(X_{\exp} - \bar{X}_{\exp})\right)}{\left(\sqrt{\sum_{i=1}^{n}(X_{the} - \bar{X}_{the})^{2} \sum_{i=1}^{n}(X_{\exp} - \bar{X}_{\exp})^{2}}\right)} \right]^{2} \tag{6}$$

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. The attained results are depicted in Figs. 2 and 3.

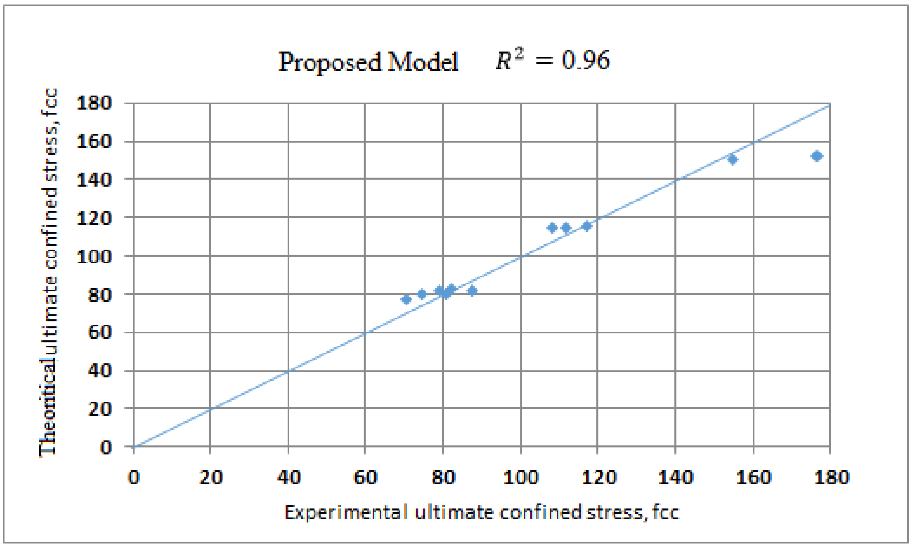

Fig 2. Correlation of the predicted values for ultimate stress with the experimental results

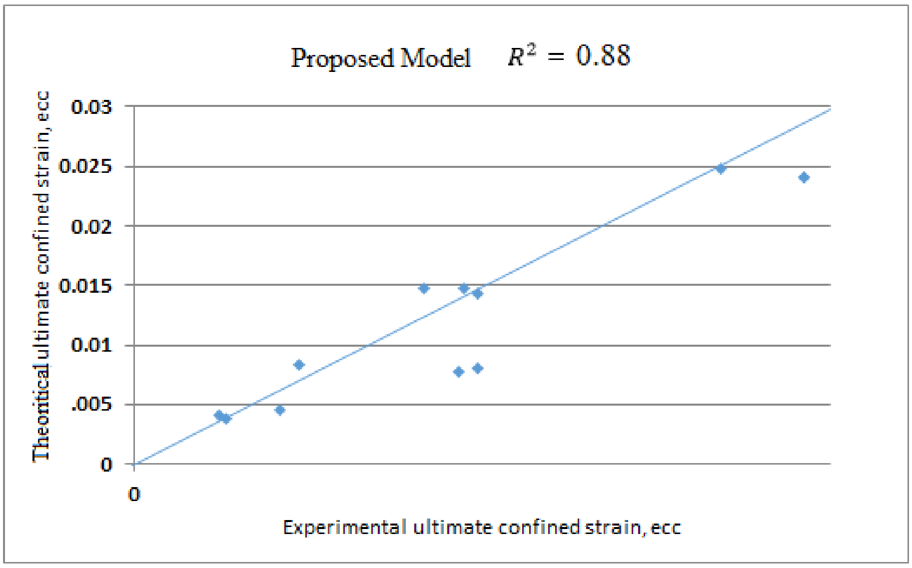

Fig 3. Correlation of the predicted values for ultimate strain with the experimental results

Moreover, to gain a better image of the accuracy of the proposed elements, ratio of the predicted values using the modified models to the experimental values for confined strength and strain are also demonstrated in Figs. 4 and 5. It is evident that the proposed modification factors provide acceptable estimations, especially for the ultimate strength.

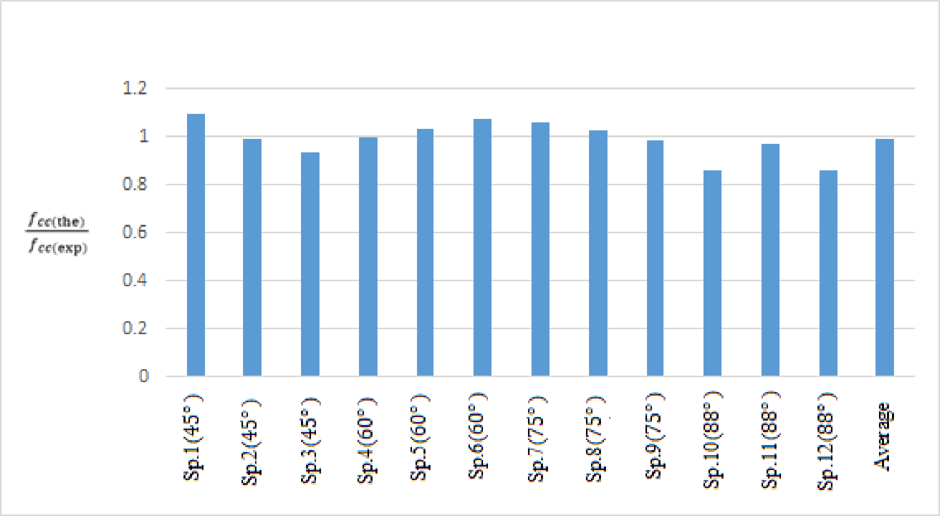

Fig 4. Ratio of the predicted values for ultimate strength to the experimental results

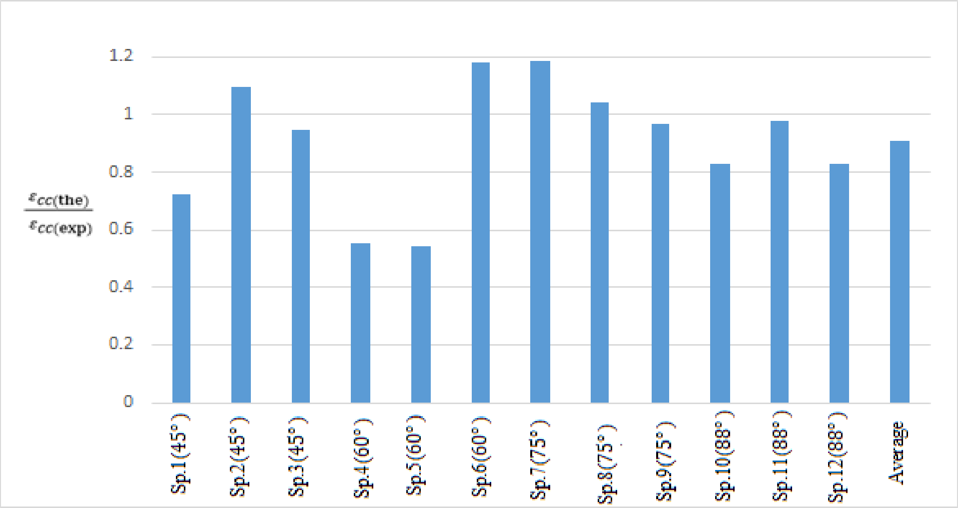

Fig 5. Ratio of the predicted values for ultimate strain to the experimental results

4. Conclusion

Due to increasing application of FRPs for strengthening and rehabilitation of concrete structures especially concrete columns, relations to determine ultimate strength and strain of confined concrete are required. Various studies showed that FRP wraps are more effective in circular sections due to uniform distribution of confinement pressure. Because of desirable characteristics of Aramid fibers, researchers and engineers tend further use of AFRPs for practical engineering applications and therefore many studies are performed on effect of AFRP wraps on concrete structures in the recent years. Accordingly, some design-oriented models are proposed to predict ultimate stress and strain of concrete columns confined by AFRP wraps. However, the main assumption in these relations is that the Aramid fibers are oriented perpendicular to the column axis. Therefore, utilization of these model for the cases that inclined fiber angles are used results in inaccurate estimations. Accordingly, in this study modification factors are proposed for ultimate stress and strain models using a database of existing experimental results and Multi-Expression Programming. Comparison of the results attained using the suggested correction factors with the experimental results demonstrated acceptable accuracy of these relations.

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