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Design oriented Hoek-Brown strength criterion and strain models in frp confined columns

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ABSTRACT: In this study, the Hoek-Brown strength criterion from rock mechanics, which was previously extended to FRP confined concrete from 7 MPa to 108 MPa, is revisited to propose design oriented models. Ultimate strengths and strains from low strength to ultra-high strength concrete (UHSC) in the wide range of unconfined strength (7 MPa to 190 MPa) are assessed via this modified strength criterion and other proposed strain models in axially loaded circular short columns. The assessment performance of the proposed strain models and the some models in the current literature are compared. Strength and strain predictions through new data for ultra-high performance concrete (UHPC) are included in this paper as well.

1 INTRODUCTION

FRP composites are used in the construction sector over two decades due to their properties such as high strength-to-weight ratio, high tensile strength and modulus, corrosion resistance and durability. FRP confinement through glass-fiber tube, frequently carbon, sometimes aramid, recently basalt sheets and some recycled materials were applied in the experiments so far (Samaan et. al.,1998; Rousakis, 2001; Dai et.al., 2011).

The experimental studies are often in the range f_{co}=20-50 MPa of unconfined compressive strength (Karbhari and Gao, 1997; Song et.al. 2013). Low strength data under 20 MPa (Ilki et.al., 2004; Pon et.al.,1998; Karbhari and Gao, 1997), and UHSC or UHPC data over 100 MPa (Miyauchi, 1999; Berthet et.al. 2005; Cui and Sheikh, 2010; Zohrevand and Mirmiran, 2011; Guler et.al. 2013) are limited compared with the other range. High compressive strength levels in the construction sector enable to reduce member sizes. FRP wrapping prevents the inherent brittle behavior due to reducing confinement effectiveness of steel in UHSC or UHPC. UHPC has different stress-strain characteristics due to steel fiber content to prevent the fragile behavior.

The Hoek-Brown criterion (Hoek et.al. 1995) provides an advantage over Mohr-Coulomb criterion for the tensile stress predictions in the compression-tension region. The Hoek-Brown criterion was first extended to FRP-confined concrete by Girgin (2009) for the compressive strength range from 7 MPa to 108 MPa. This study focuses to propose to revisit this modified criterion and to develop new models covering stresses and strains. Database was updated (7 MPa to 190 MPa) with new data covering UHSC and UHPC from the current literature. Stresses and strains agree with experimental results.

2 STRENGTH AND STRAIN MODELS FOR FRP CONFINEMENT

2.1 Confinement with FRP

Under triaxial compressive stresses, the columns are subjected to major compressive stresses σ_1 uniformly applied along the axial axis of the column and minor principal stresses (lateral confining pressure) σ_3 (f_l) (Fig.1) enhancing the unconfined compressive strength of concrete (σ_c, f_{co}). Passive confinement pressure σ_3 (f_l) can be presently provided by FRP confinement (sheets and tubes) instead of steel confinement as well. f_l (σ_3) is expressed in terms of hoop tensile strength of FRP (σ_{frp} or f_{frp})

$$f_l = \sigma_3 = \frac{2t\,\sigma_{frp}}{D} \tag{1}$$

or in terms of FRP ultimate strain (ε_f)

$$f_l = \frac{2tE_f\,\varepsilon_f}{D} = \frac{1}{2}\rho_f E_f \varepsilon_f\,,\quad \rho_f = \frac{4t}{D} \tag{2}$$

where D, E_f, ρ_f, t denote the diameter of concrete core, Young's modulus, volumetric ratio and thickness of FRP, respectively.

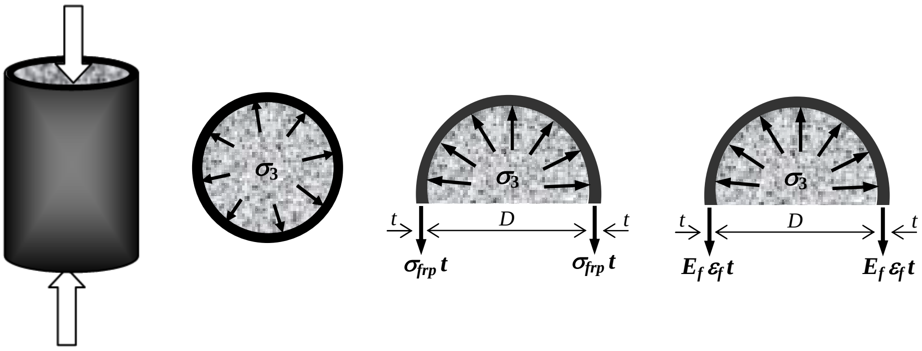


Figure 1 Development of confining pressure in FRP confined concrete

In the literature, several strength models are available, however the models predicting both stress and strain are more limited. Specific design oriented models assessing ultimate strengths and strains in circular short columns are given in Table 1.

Table 1. Strength and strain models in circular sections

Source	Strength model	Strain model
Fardis and Khalili (1981) -strength model based on Richart et.al.(1929) (f_{co}=20-50 MPa)	$\frac{f_{cc}}{f_{co}} = 1 + 4.1\frac{f_l}{f_{co}}$	$\varepsilon_{cu} = \varepsilon_{co} + 0.0005\frac{E_l}{f_{co}}$
Mander et al.(1988)[a] Saadatmanesh et.al.(1994)	$\frac{f_{cc}}{f'_{co}} = 2.254\sqrt{1 + 7.94\frac{f_l}{f'_{co}}} - 2\frac{f_l}{f'_{co}} - 1.254$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1 + 5\left(\frac{f_{cc}}{f_{co}} - 1\right)$
ACI 440 (2008)		$\varepsilon_{cu} = \frac{1.71(5f_{cc} - 4f_{co})}{E_c}$
Karbhari and Gao (1997) (f_{co}= 38 MPa)	$\frac{f_{cc}}{f_{co}} = 1 + 2.1\left(\frac{f_l}{f_{co}}\right)^{0.87}$ Model II	$\varepsilon_{cu} = \varepsilon_{co} + 0.01\frac{f_l}{f_{co}}$
Kono et.al. (1998) (f_{co}=32-35 MPa)	$\frac{f_{cc}}{f_{co}} = 1 + 0.0572\,f_l$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 1 + 0.28\,f_l$

Saafi et. al. (1999) (f_{co}= 38 MPa)	$\frac{f_{cc}}{f_{co}}=1+2.2\left(\frac{f_l}{f_{co}}\right)^{0.84}$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}=1+\left(537\varepsilon_f+2.6\right)\left(\frac{f_{cc}}{f_{co}}-1\right)$
Spoelstra and Monti (1999) (f_{co}= 30-50 MPa)	$\frac{f_{cc}}{f_{co}}=0.2+3\left(\frac{f_l}{f_{co}}\right)^{0.5}$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}=2+1.25\frac{E_{co}}{f_{co}}\varepsilon_f\left(\frac{f_l}{f_{co}}\right)^{0.5}$
Xiao and Wu (2000) (f_{co}= 34-55 MPa, CFRP)	$\frac{f_{cc}}{f_{co}}=1.1+\left[4.1-0.75\left(f_{co}^2/E_l\right)\right]\frac{f_l}{f_{co}}$	$\varepsilon_{cu}=\frac{\varepsilon_f-0.0005}{7\left(f_{co}/E_l\right)^{0.8}}$
Toutanji (1999) -modified- (f_{co}= 31 MPa)	$\frac{f_{cc}}{f_{co}}=1+2.3\left(\frac{f_l}{f_{co}}\right)^{0.85}$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}=1+\left(310.57\varepsilon_f+1.9\right)\left(\frac{f_{cc}}{f_{co}}-1\right)$
Lam and Teng (2003) (f_{co}= 27-55 MPa)	$\frac{f_{cc}}{f_{co}}=1+3.3\frac{f_{l,a}}{f_{co}}\ (\frac{f_{l,a}}{f_{co}}\geq 0.07)$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}=1.75+12\frac{f_{l,a}}{f_{co}}\left(\frac{\varepsilon_{h,u}}{\varepsilon_{co}}\right)^{0.45}$
Teng et.al. (2009) (f_{co}= 38-46 MPa)	$\frac{f_{cc}}{f_{co}}=1+3.5\left(\rho_k-0.01\right)\rho_\varepsilon\ \ (\rho_k\geq 0.01)$ $\rho_k=\frac{2E_f t\,\varepsilon_{co}}{D\,f_{co}},\rho_\varepsilon=\frac{0.586\,\varepsilon_f}{\varepsilon_{co}}$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}=1.75+6.5\rho_k^{0.8}\rho_\varepsilon^{1.45}$
Benzaid et. al. (2010) (f_{co}= 29-62 MPa, CFRP)	$\frac{f_{cc}}{f_{co}}=1+1.6\frac{f_l}{f_{co}}$, $\frac{f_{cc}}{f_{co}}=1+2.2\frac{f_{l,a}}{f_{co}}$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}=2+5.5\frac{f_l}{f_{co}}$, $\frac{\varepsilon_{cu}}{\varepsilon_{co}}=2+7.6\frac{f_{l,a}}{f_{co}}$
Rousakis et.al. (2012) (f_{co}= 9-170 MPa)	$\frac{f_{cc}}{f_{co}}=1+\left(\frac{\rho_f E_f}{f_{co}}\right).\left(\frac{\alpha E_f 10^{-6}}{E_{f\mu}}+\beta\right)^{a}$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}=1+24.8\frac{4E_f t}{D\,f_{co}}\left(\frac{-0.45E_f 10^{-6}}{E_{f\mu}}+0.0223\right).\left(\frac{40E_f t}{E_{f\mu}D}\right)^{-0.16}$
Ozbakkaloglu and Lim (2013)	$\frac{f_{cc}}{f_{co}}=1+3.64\frac{f_{l,a}}{f_{co}}\ (CFRP)$ $\frac{f_{cc}}{f_{co}}=1+2.64\frac{f_{l,a}}{f_{co}}\ (GFRP)$	$\frac{\varepsilon_{cu}}{\varepsilon_{co}}=2+17.41\frac{f_{l,a}}{f_{co}}\ (CFRP)$ $\frac{\varepsilon_{cu}}{\varepsilon_{co}}=2+24.47\frac{f_{l,a}}{f_{co}}\ (GFRP)$

[a] $\rho_f = 4t_f/d$, $E_{f\mu}$=10 MPa (for units compliance); α=-0.336, β=0.0223 for FRP sheets ; α=-0.23, β=0.0195 for FRP tube
Y= f_{cc}/f_{co}-1, X=$\rho_f E_f / f_{co}$,Y=AX, carbon: A= 0.0151(E_f =234 GPa), 0.0093(E_f =377 GPa), 0.0021(E_f =640 GPa), glass: A=0.0187(E_f =80.1 GPa)

2.2 Strength Models

Earlier models for FRP confinement (Table 1) were proposed based on steel-confined concrete (Fardis and Khalili,1981; Mander et.al. 1988;Saadatmanesh et.al. 1994). Most models for steel and FRP confined concrete are based on the Mohr-Coulomb criterion (Richart et.al. 1929; Saafi et.al. 1999; Spoelstra and Monti,1999; Benzaid et.al. 2010).

Hoek-Brown and Johnston failure criteria from rock mechanics were firstly extended and modified for FRP confined concrete to precisely predict ultimate strength (Table 2) by including common FRP confinement types (CFRP, GFRP, AFRP sheets; and GFRP tube) in a wide range (7 to 108 MPa). The Integral Absolute Error (IAE) in two modified criteria is under 6% in the each specific range of overall averaged data (*n*=135). According to the verification results, these criteria can be successfully used for the reliable ultimate strength assessments. In the previous studies (Girgin 2009, 2014), the prediction performances of the strength models (Table 2 and other models) in the current literature were investigated based on each strength range. For this reason, herein, the assessment performances they will not be mentioned again. In passing, the performance assessment based on strength range may be more meaningful compared with investigating one error ratio (IAE, AAE etc.) through overall data in the current literature.

Recent HSC (40-100 MPa) and UHSC (100-150 MPa) data added to database were used to reverify *m* coefficient. The expressions of *m* coefficient (Table 2) were not changed, *m*=0.1 is valid from f_{co}=82 MPa to 114 MPa according to the comparisons in this study (Fig.2a). Meanwhile comparable UHSC data is available up to 113.6 MPa.

Table 2. Modified strength models from rock mechanics

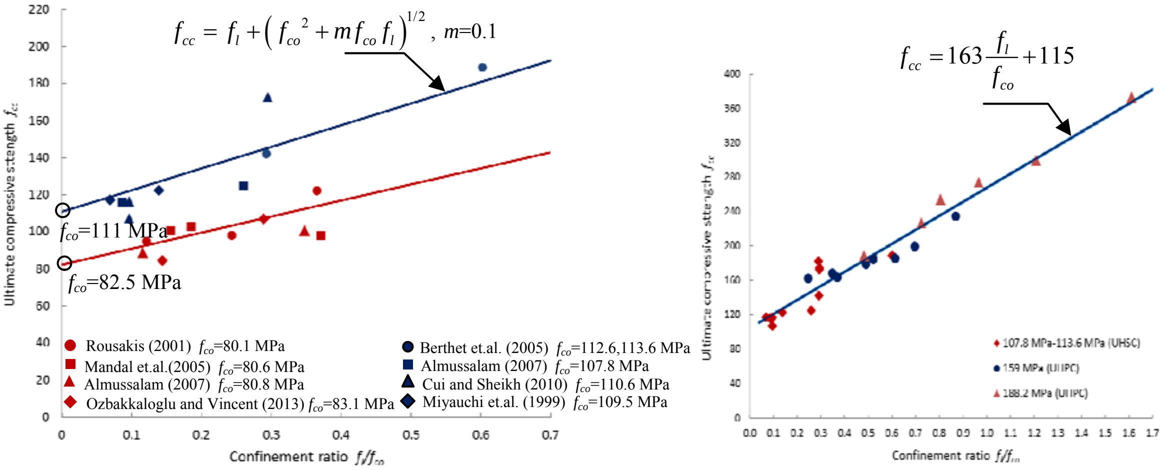
	Failure criterion for rock	Modified form for FRP confinement of concrete
Girgin (2009)	Hoek-Brown (Hoek et.al. 1995) $\sigma_1=\sigma_3+\sigma_c\left(m\dfrac{\sigma_3}{\sigma_c}+s\right)^{0.5}$ $\sigma_c \geq 20$ MPa	$f_{cc}=f_l+\left(sf_{co}^{\ 2}+mf_{co}f_l\right)^{1/2}$ s=1 for intact rock or undamaged concrete m=2.9 (f_{co}=7 MPa to18 MPa) m= 6.34–0.076 f_{co} (f_{co}=20 MPa to 82 MPa) m=0.1 (f_{co}=82 MPa to 108 MPa)
Girgin (2014)	Johnston (Johnston, 1985) $\dfrac{\sigma_1}{\sigma_c}=\left(1+\dfrac{M}{B}.\dfrac{\sigma_3}{\sigma_c}\right)^B$	$\dfrac{f_{cc}}{f_{co}}=\left(1+\dfrac{M}{B}.\dfrac{f_l}{f_{co}}\right)^B$ $B=1-0.0172\left(\log\ f_{co}\right)^2$, f_{co} in kPa $M=0.0035f_{co}^2-0.056f_{co}+2.83$ (f_{co}=7 MPa to 25 MPa) $M=0.0003f_{co}^2-0.076f_{co}+5.46$ (f_{co}=25 MPa to 108 MPa)

As for UHPC, a practical relationship is proposed by covering UHSC data as well as UHPC data (Miyauchi et.al. 1999; Cui and Sheikh, 2010; Berthet et.al. 2005; Zohrevand and Mirmiran, 2011; Ozbakkaloglu and Vincent, 2013; Guler et.al.,2013) from f_{co} =108 MPa to 188 MPa for f_l/f_{co}= 0.07 to 1.6 (Fig. 2b) and all FRP types mentioned above with high accuracy

$$f_{cc}=163\frac{f_l}{f_{co}}+105\ (n\text{=25, }R\text{=0.975, IAE=5.9 \%, AAE=6.4 \%}) \tag{3}$$

in which IAE (Integral Absolute Error) and AAE (Average Absolute Error) are

$$\text{IAE=}\frac{\sum\left|o_i-p_i\right|}{\sum o_i},\ \text{AAE=}\frac{\sum\left|(o_i-p_i)/o_i\right|}{n},\ (o_i\text{=observed, }p_i\text{=predicted})$$



(a) (b)

Figure 2 (a) Verification of modified Hoek-Brown modified criterion for very high compressive strength levels (b) Proposed linear relationship for UHSC and UHPC

2.3 Strain Models

The ultimate strain of confined concrete ε_{cu} is generally defined in terms of ε_{co} and as a function of f_l , f_l/f_{co}, f_{cc}/f_{co} ,ε_f and some additional parameters such as elastic modulus of concrete (E_c), confinement modulus (E_l) or volumetric ratio (ρ_f). Meanwhile, there is a reduction factor (k) (Spoelstra and Monti, 1999; Pessiki et. al.,2001) between ε_f and the hoop rupture strain $\varepsilon_{h,u}$

$$\varepsilon_{h,u}= k\varepsilon_f \tag{4}$$

CFRP confined circular specimens cover the widest test data in the literature. For this reason, the database was mainly compiled with the experimental results of CFRP (n=177) wrapped circular specimens to enhance reliability. More limited data for GFRP wrapped specimens (n=62) were also included to the database. The available ultimate strain data are in the range f_{co}=18 MPa to 188 MPa. The following relationship in Eurocode 2 (2004) was used for the prediction of ε_{co}

$$\varepsilon_{co} = \frac{0.7}{1000} f_{co}^{0.31} \tag{5}$$

The assessment performances of some analytical models (Table 1) were compared with the experimental results in Fig. 3. It is noted that Ozbakkaloglu and Lim (2013)'s model is based on actual hoop rupture strain values ($\varepsilon_{h,u}$) and confining pressure ($f_{l,a}$) while other models used FRP ultimate strains (ε_f) and theoretical pressures (f_l). The assessment performance of any model in Table 1 was investigated based on the database not the range of that model. As almost all the models are deviated at or over about f_{co}=100 MPa, the experimental data in the model comparisons was limited with upper 110 MPa strength level. Only the proposed models in this study take all database into consideration.

Generally, a higher scattering in ultimate strains (ε_{cu}) in the database is under consideration compared with those of ultimate strengths (f_{cc}). In this study, to compare the actual models and to develop practical relationships, some test results significantly deviated from the general trend were discarded from the analyses. The main target is to propose practical models (Table 3) through main parameters (f_l, f_l/f_{co}, f_{cc}/f_{co}) predicting the ultimate strains with high accuracy by using currently available fiber or jacket data It is noted there are discontinuities in the strength ranges of limited GFRP wrapped specimens.

Table 3 The proposed strain models developed in this study

Parameter	Relationship	Data range	IAE %	AAE %	Sheet type
f_l	$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 4.3*10^{-5} f_l^3 - 0.008 f_l^2 + 0.57 f_l + 1$	15 MPa $\leq f_{co} <$ 50 MPa	15.8	15.9	CFRP
			16.4	17.6	GFRP
f_l/f_{co}	$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = -4.24\left(\frac{f_l}{f_{co}}\right)^2 + 15.42\left(\frac{f_l}{f_{co}}\right) + 2.23$	15 MP a $\leq f_{co} \leq$50 MPa 0.01$\leq f_l/f_{co} \leq$ 8.1	See Fig. 3		
	$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = -2.62\left(\frac{f_l}{f_{co}}\right)^2 + 10.94\left(\frac{f_l}{f_{co}}\right) + 1.0$	50 MPa $< f_{co} \leq$109 MPa (CFRP) 0.07$\leq f_l/f_{co} \leq$ 1.14			
	$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = -3.42\left(\frac{f_l}{f_{co}}\right)^2 + 12.7\left(\frac{f_l}{f_{co}}\right) + 0.27$	80 MPa $< f_{co} \leq$159 MPa* (GFRP) 0.10$\leq f_l/f_{co} \leq$ 0.61			
	$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 0.57\left(\frac{f_l}{f_{co}}\right) + 1$	109 MPa $< f_{co} \leq$170 MPa*(CFRP) 0.07$\leq f_l/f_{co} \leq$ 8.14			
f_{cc}/f_{co}	$\frac{\varepsilon_{cu}}{\varepsilon_{co}} = 4.46\left(\frac{f_{cc}}{f_{co}}\right) - 2.14$	15 MPa $< f_{co} \leq$103 MPa (CFRP) 1.02$\leq f_{cc}/f_{co} \leq$ 4.24	15.4	14.2	CFRP

* UHPC data was also included.

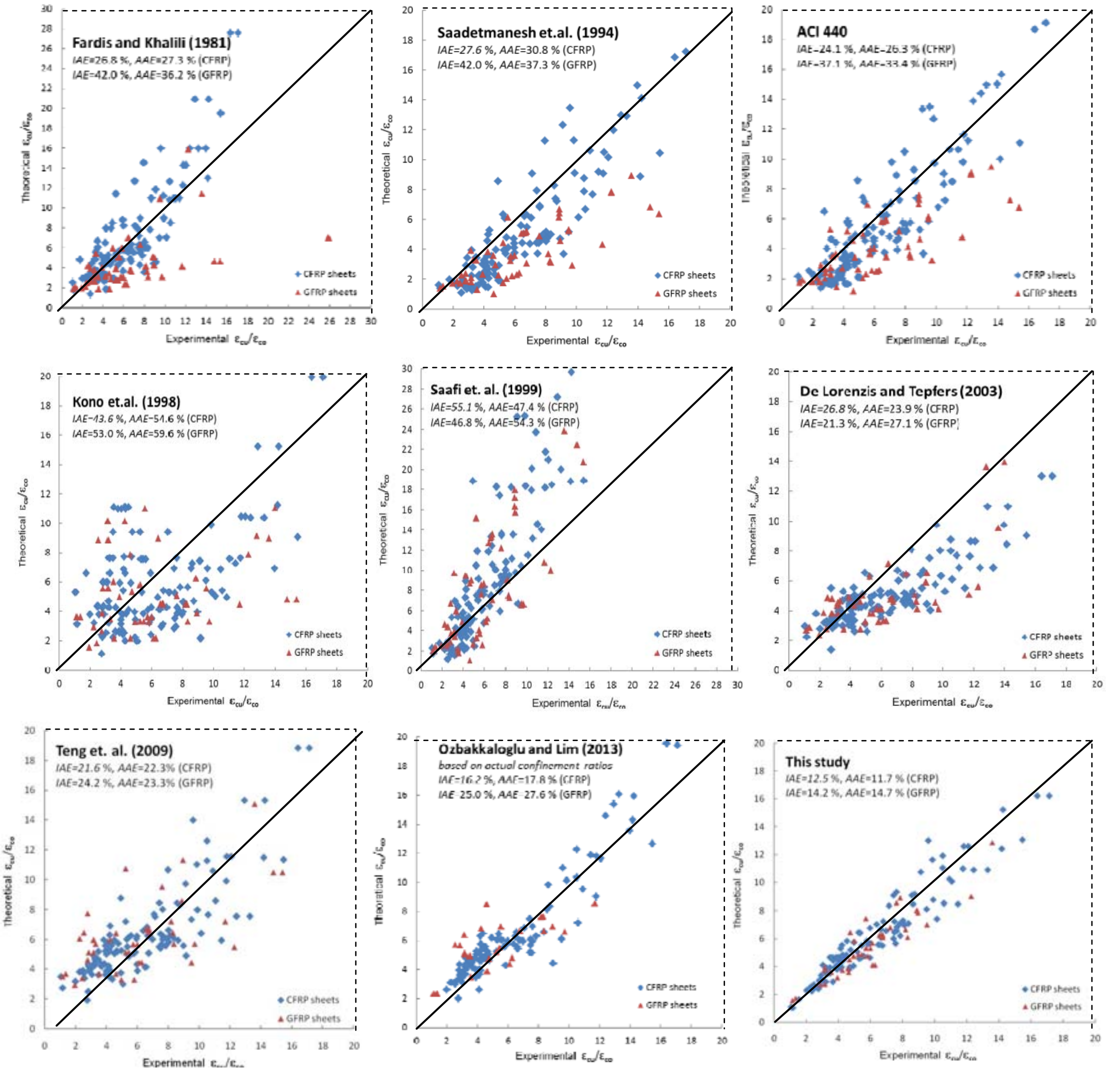


Figure 3 Assessment performance of models for the short columns confined with CFRP and GFRP wraps in the current literature and proposed model

It is seen from. Fig. 3 that the developed strain model in this study may predict the ultimate strains of CFRP and GFRP confined specimens.

3. RESULTS

In this study, the modified Hoek-Brown criterion is revisited and generalized with other stress and strain models developed in this study to propose a design oriented model for FRP confined circular short columns. Ultimate strength and strain estimations are included into this paper. A database of very wide-range of unconfined strength (7 to 190 MPa) are used in the analyses. The successful estimations for ultra-high strength (UHSC) and ultra-high performance concrete (UHPC) are considered in this paper as well.

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