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Modified failure criteria from rock mechanics to predict the ultimate strength of FRP confined column

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ABSTRACT: In this study, the models from rock mechanics were extended to concrete to assess the ultimate compressive strength of axially loaded circular columns especially confined with fiber-reinforced polymer (FRP) composites. One of the models is based on Mohr-Coulomb failure criterion used by many authors as well. In addition two models essentially developed for intact rocks, Hoek-Brown and Johnston failure criteria, were extended to confined concrete and verified through the wide-range experimental data for short columns with the compressive strengths from 7 to 170 MPa and high confinement ratios up to 2.0. All models are in good agreement with experimental data for all confinement levels and concrete strengths.

1 INTRODUCTION

FRP composites are suitable for use in coastal and marine structures as well as civil infrastructure facilities due to their properties such as high strength-to-weight ratio, high-tensile strength and modulus, corrosion resistance and durability. FRP confinement enhances the seismic performance, energy absorption capacity and ductility. FRP jacket is applied for seismic rehabilitation of damaged reinforced concrete structures (e.g. pier column, fender pile in marine environment). FRP tube also provides a permanent formwork, savings in transportation costs and construction effort as well.

The study encompasses to predict the ultimate strength of axially loaded circular columns via modified failure criteria. In addition to the widely used approach based on Mohr-Coulomb criterion, two failure criteria from rock mechanics, Hoek-Brown criterion (Hoek et.al.1995) and Johnston criterion (Johnston,1985) are modified to confined concrete, especially to FRP confinement. The averaged database comprises total n=131 data having the cylinder compressive strengths 7 MPa to 170 MPa, i.e. n=103 data for FRP-wrapped concrete cylinders and n=28 data for FRP tube encased cylinders. The modified failure criteria from rock mechanics can be also used successfully with respect to verification results.

2 MODIFIED FAILURE CRITERIA

2.1 General

In this study, the Mohr-Coulomb criterion used by many authors widely and two failure criteria, Hoek-Brown and Johnston, from rock mechanics are focused and modified to FRP columns.

Table 1. Failure Criteria extended to confined concrete from soil and rock mechanics

	Failure Criteria	Range	Confinement effectiveness
Mohr-Coulomb	$\sigma_1 = \frac{2c\cos\phi}{1-\sin\phi} + \frac{1+\sin\phi}{1-\sin\phi}\sigma_3$	Triaxial soil data	$k = \frac{1+\sin\phi}{1-\sin\phi}$
	$\frac{f_{cc}}{f_{co}} = 1 + k\frac{f_l}{f_{co}}$	Confined concrete	k=4.1 (Richart et.al.1929)
Hoek-Brown	$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m\frac{\sigma_3}{\sigma_{ci}} + s\right)^{0.5}$	For rocks ($\sigma_{ci} \geq 20$ MPa)	m=15 for sandstone and quartzite for intact rock or concrete (s=1)
	$f_{cc} = f_l + \left(f_{co}^2 + m.f_{co}.f_l\right)^{1/2}$		$m = \frac{(f_{cc}-f_l)^2 - f_{co}^2}{f_{co}.f_l}$
Johnston	$\frac{\sigma_1}{\sigma_{ci}} = \left(1 + \frac{M}{B}.\frac{\sigma_3}{\sigma_{ci}}\right)^B$	For the range of soil to rock ($0.008 \leq \sigma_{ci} \leq 600$ MPa)	$M = 2.065 + C\left(\log\sigma_{ci}\right)^2$ C is a function of the rock type (C=0.270 for sandstone and quartzite)
	$\frac{f_{cc}}{f_{co}} = \left(1 + \frac{M}{B}.\frac{f_l}{f_{co}}\right)^B$		$B = 1 - 0.0172\left(\log\sigma_{ci}\right)^2$

ϕ : internal-friction angle , c : cohesive strength of soil, M, B, m : material coefficients
σ_{ci} , f_{co} : uniaxial compressive strength of intact rock specimens and concrete cylinder strength, respectively
σ_3 , f_l: minor principal stress or confining pressure, σ_1 , f_{cc}: major principal stress at failure or ultimate strength

2.2 Mohr Coulomb Failure Criterion and confined concrete

Classical k coefficient proposed by Richart et.al. (1929) is 4.1 for actively and passively confined circular concrete sections. Later, Saatcioglu and Razvi (1992) expressed that k coefficient decreases with increasing confining pressure by approaching a constant value in steel reinforced concrete (RC). Lam and Teng (2002) showed that k is independent of the type of FRP confinement. In this study, it is focused to the experimental data of FRP wrapped specimen compiled from the literature (Figure 1). It is interesting that two significantly different trends are observed. In the first trend, the value of k is high in low confinement levels and declines to a constant value in high confinement levels. As a second trend, data is quite scattered in the low confinement levels. It may be suggested that k has either a constant value of about 2 or a variation displayed with the dashed line. The dashed line converges towards the first trend at medium confinement levels. Spoelstra and Monti (1999) stated that if f_l/f_{co} ratio is smaller than 0.07, FRP wrapped concrete behaves similar to that of unconfined -control- concrete due to insufficient confinement. In this study, the variation of k reveals that the lack of confinement was generally observed in one-layer FRP wrapped cylinder specimens and partially in high strength levels. After excluding scattering data, the regression analysis of the first trend was conducted with n=103 data and an equation is derived with the correlation coefficient of R=0.95 and IAE ratio (Integral Absolute Error) of 4.4-8.9 %.

$$k = 2.109\left(\frac{f_l}{f_{co}}\right)^{-0.217} \qquad (1)$$

The variation of k as the nonlinear function of f_l / f_{co} is plotted in Figure 1. As for the high confinement levels of $f_l / f_{co} \geq 1$, k value converges to about 1.8 as well. The same trend is valid for FRP tube encased specimens (n=28) exactly. In Turkish Earthquake Code (2007), k coefficient was defined to be constant (k=2.4) for FRP confinement. The variation between the strengthening ratio and confinement ratio concerning all the FRP confinement types is displayed in Figure 2.

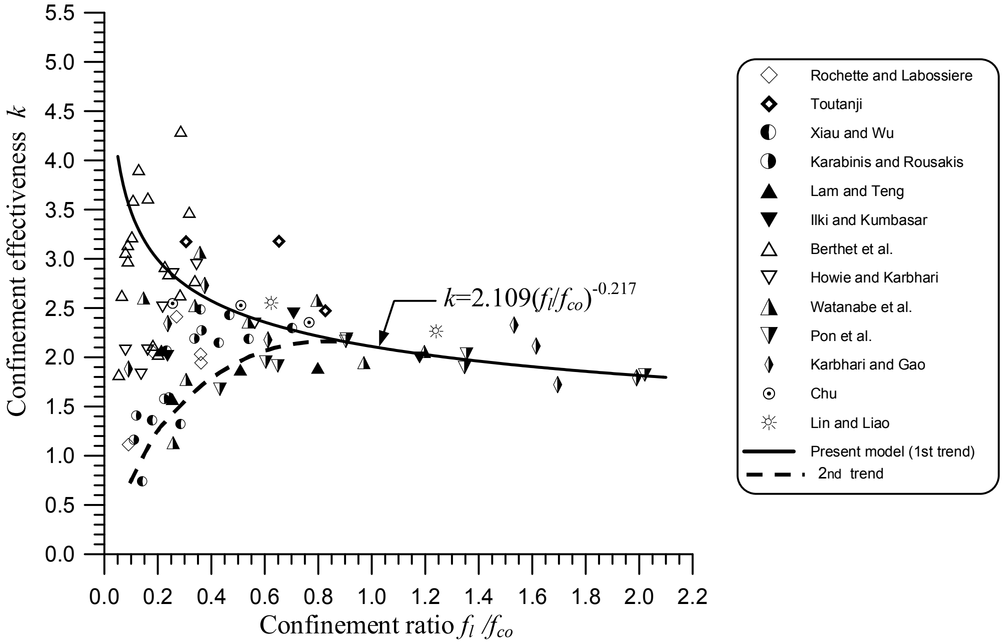


Figure 1. Variation of confinement effectiveness k with confinement ratio f_l / f_{co} for FRP wrapped specimens.

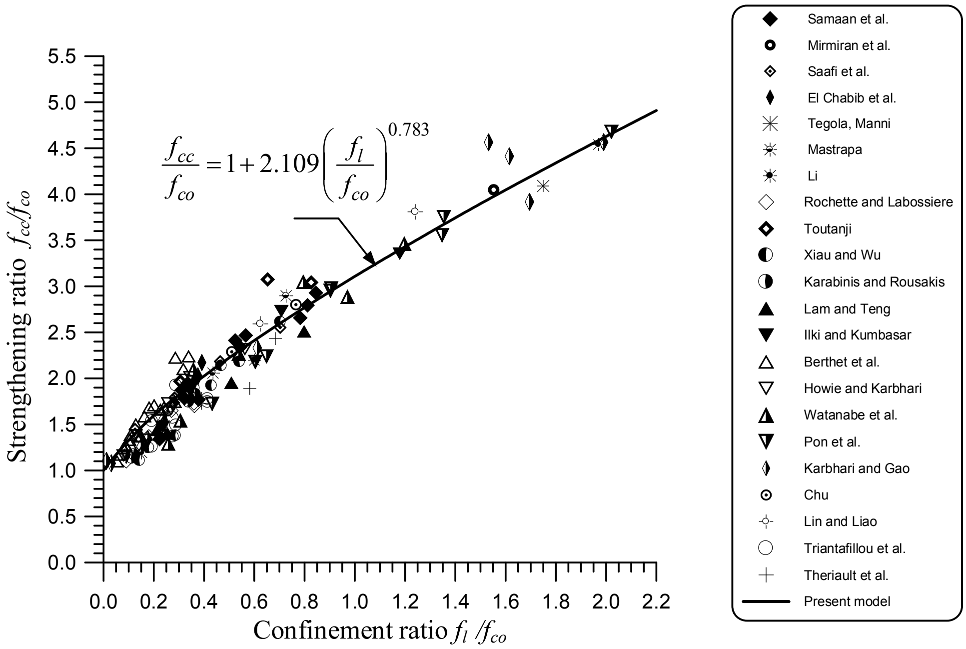
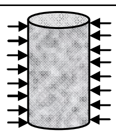


Figure 2. Variation of f_{cc} / f_{co} with f_l / f_{co} for FRP wrapped and FRP tube encased specimens

2.3 Hoek-Brown Failure Criterion and confined concrete

In this failure criterion adapted from rock mechanics, the first step is to predict the value of the *m* constant in Table 1. The *m* values predicted for cylinder specimens according to the strength ranges from the wide range experimental data are displayed in Table 2 for different confining techniques. While *m* is in the range 4.8 to 3.3 for normal-strength concrete (20 to 40 MPa), it has a very low value (*m*=0.1) in the high-strength concrete especially over 80 MPa (Girgin, 2009). This trend can be attributed to the close similarity between *m* and confinement effectiveness coefficient *k*. The highest *m* value (*m*=13;Girgin et.al.,2007) is under consideration for actively confined concrete and *m* value approaches to the lower range of rocks. The variations between strengthening ratio and confinement ratio are displayed for confined concrete by different ways and rock specimens in Figure 3.

Table 2. The variation of predicted *m* constant through different confining techniques

Confining material	Confined concrete	f_{co}	m	Number of data	IAE %	$\overline{\Delta}$
FRP wrapped or encased tube		$7 \leq f_{co} \leq 18$ MPa	2.9	24	4.2	+4.5, -4.2
		$20 \leq f_{co} \leq 82$ MPa	$6.34-0.076 f_{co}$	104	4.6	+4.6 , -4.9
		$82 < f_{co} \leq 170$ MPa	0.1	7	5.2	+5.2, -5.5
Steel spiral/ hoop +FRP jacket		$15 \leq f_{co} < 25$ MPa	6.5	11	3.4	+3.1, -2.6
Active pressure		$60 \leq f_{co} < 132$ MPa	13	71	4.8	+4.1, -6.7

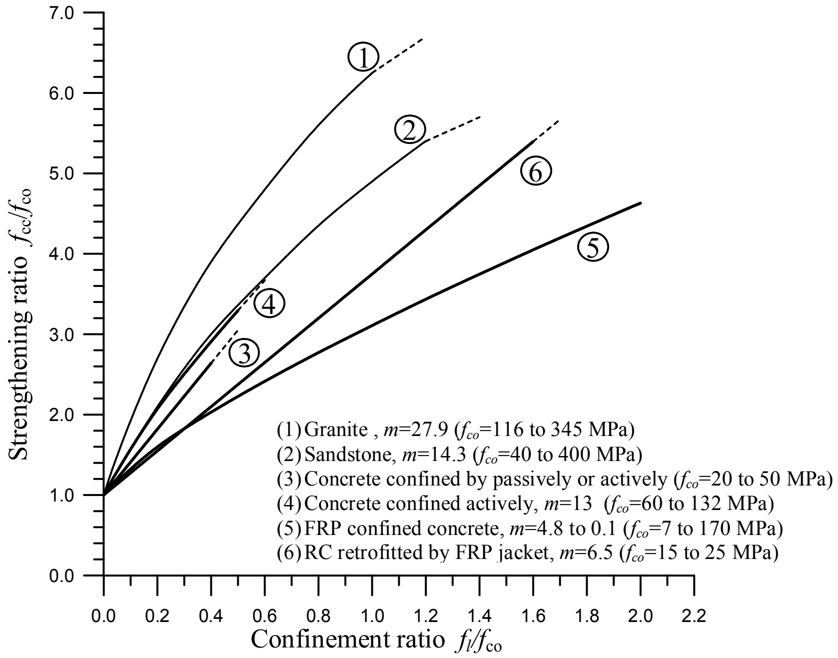


Figure 3. Failure envelopes of some intact rock specimens and concrete confined by different confining materials via Hoek-Brown failure criterion (Girgin, 2009)

2.4 Johnston Failure Criterion and Confined Concrete

This failure criterion covers a wide range of compressive strengths from clay soils to extremely hard rocks from 0.008 to 600 MPa. By extending to confined concrete, the failure envelope can be established easily by predicting *B* and *M* coefficients. The material coefficient *M* may be predicted as one value having a minimum error for all data. Herein, the material coefficient *M* is assigned to be 3.1 with min. IAE ratio of 5.7% for FRP confined concrete (*n*=131). It is interesting that *M* coefficient also stands for the lower range of limestone and sandstone within all the rock types. B coefficient may be predicted from Eq.(2). The practical importance of this equation is directly to estimate *B* coefficient via cylinder compressive strengths f_{co}

$$\frac{f_{cc}}{f_{co}}=\left(1+\frac{3.1}{B}.\frac{f_l}{f_{co}}\right)^B \tag{2}$$

In the analysis it is determined that *B* coefficient varies from 0.74 to 0.52 for the compressive strengths range from 7 MPa to 170 MPa and the IAE ratios are in the range of 4.0-8.2%. Johnston's criterion is shown in Figure 4 with other failure criteria.

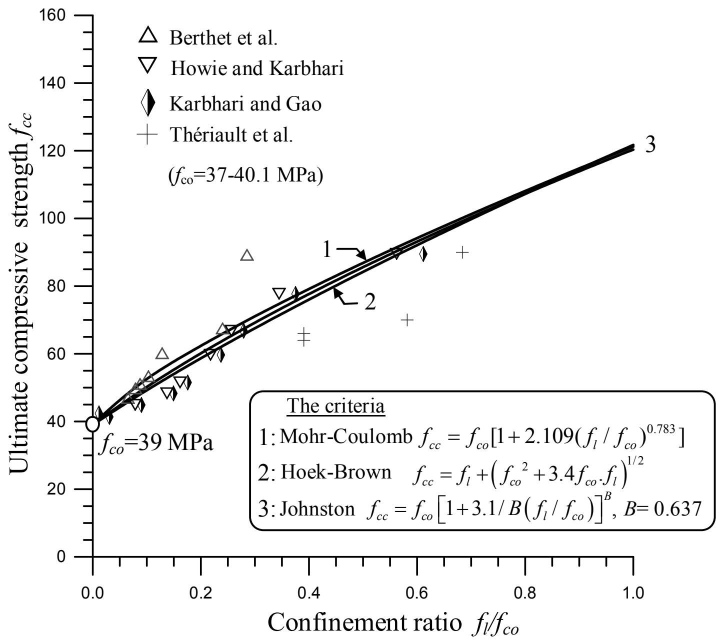


Figure 4. Failure envelopes (f_{co}=39 MPa) corresponding to confinement ratios of FRP confined concrete

3. CONCLUSIONS

The modified models from rock mechanics were extended to FRP confined concrete and the results are in a good agreement for the widest range data (7 to 170 MPa) so far. As for the model based on Mohr-Coulomb criterion, insufficient confinement may indicate low *k* values possibly due to the lack of FRP confinement, otherwise the size effect or very high compressive strength levels. In high confinement levels the *k* value converges to a constant value about 1.8. The material constant *m* of Hoek-Brown failure criterion is predicted in the range of *m*=13-0.1 concerning confinement type and strength range. The material coefficient *B* of Johnston failure criterion is predicted from 0.74 to 0.52 for all the compressive strength range. As a general result, the ultimate strength in concrete confined by different confining materials can be successfully predicted through the modified failure criteria from rock mechanics by only knowing cylinder compressive strength.

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