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Calibration of Reduction Factor for Concrete Columns Strengthened with Unidirectional Fiber-Reinforced Wrapping

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Abstract

Strengthening with fiber-reinforced polymer (FRP) wrapping is a well-established method of retorifiting or upgrading existing concrete columns. The available test data cooreponding to FRP wrapped concrete columns has expanded significantly due to the growing interest in the application of FRP confinment. However, the reduction factors suggested by the applicable design guidelines were developed more than a decade ago based on a limited data set. In this study, reduction factors for FRP confined concrete columns were calibrated using a reliablity-bsed approach. Approximetaly eight hundred experimental tests of FRP wrapped concrete columns with various thicknesses, modulus of elasticity, ultimate tensile strength, number of FRP layers, column diameter, and column compressive strength were considered in the reduction factor calibration. Multiple reduction factors were suggested based on a practical range of target reliability indices. Also, the reliablity indicies that were used in calibrating the reduction factors in ACI 440 were assessed using the database considered in this study. The analysis results showed that the current reduction factor proposed by ACI 440 is adequate for achieving a target reliablity index of 3.5.

Keywords: Reliability, Resistance Factor, Concrete Columns, FRP, Wrap, Strengthening

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Introduction

The current design of fiber-reinforced polymer (FRP) wrapping for concrete columns, based on ACI 440.2R [1], considers load and resistance factor design (LRFD) method which involves load and resistance reduction factors. The reduction factor for FRP strengthened concrete columns, ϕ, is adopted from ACI 318 [2], which was developed for steel reinforced columns. An additional resistance factor, ψ, is also applied to the FRP material to account for the material variability. The calibration of ψ was established based on Monte Carlo simulations, and a factor of 0.95 was recommended by ACI 440.2R [1] to account for the FRP effect for fully wrapped concrete columns.
Optimum designs should aim at balancing the safety and economy. The optimization process can be conducted by utilizing reliability-based methods in calibrating refined material or system reduction factors. Unbalancing the safety and economy aspects in the design process may lead to overdesigning structures in which the margin of safety could be multiple times that what is necessary to achieve a target level of design safety. For example, Sadeghian et al. [3] found that the actual reliability index for tested concrete-filled FRP tubes (CFFTs), was 4.05 and 4.95 for under- and over-reinforced CFFTs, respectively, while the target reliability index ranged from 3.0 to 4.0. With the increasing number of data related to testing FRP confined concrete columns, a revisit to the calibration of FRP wrapped concrete column reduction factor is deemed necessary to validate the current value adopted by the ACI 44.2R [1] code. The objective of the present study is to calibrate the reduction factor for FRP wrapped concrete columns based on an extensive database with approximately 800 experimental tests gathered from literature.

Resistance Factor Calibration

The reduction factor was calibrated using first-order second-moment method (FOSM) due to its alignment with ACI reliability-based calibration methods and accuracy [4]. By considering dead load, live load, and the structural resistance as lognormally distributed random variables, the reduction factor can be calculated using the following equation:

$$\phi = \frac{\lambda_R\left(\frac{\gamma_D Q_D}{Q_L}+\gamma_L\right)\sqrt{\frac{1+COV_{Q_D}^2+COV_{Q_L}^2}{1+COV_R^2}}}{\left(\frac{\lambda_{Q_D} Q_D}{Q_L}+\lambda_{Q_L}\right)e^{\beta\sqrt{ln\left[\left(1+COV_R^2\right)\left(1+COV_{Q_D}^2+COV_{Q_L}^2\right)\right]}}} \quad (1)$$

where:

COV_R, COV_{Q_D}, COV_{Q_L}	= The coefficient of variations of resistance, dead load, and live load [-]
Q_D/Q_L	= The ratio of dead load to live load [-]
γ_D, γ_L	= Dead and live load factors [-]
β	= Reliability index [-]
λ_R, λ_{Q_D}, λ_{Q_L}	= The bias ratios of resistance, dead load, and live load [-]
ϕ	= Reduction factor [-]

The load factors were set to 1.2 and 1.6 for dead and live loads, respectively, to be compatible with ACI 318-14 [2]. The target reliability index suggested by ACI 4402R-17 [1] ranges between 3.0 to 3.5. The ratio of dead-to-live load was considered to range between 0.2 to 4.0. The dead-to-live load ratio of 4 was selected based on a recent survey that considered actual service live load measurements [4]. The bias factor and coefficient of variation of the dead load were considered as 1.05 and 0.1, respectively, while the bias factor and the coefficient of variation of the live load were 0.9 and 0.17, respectively [4]. To calibrate the reduction factor in the current study, a database [5, 6] consisting of approximately 800 experimental tests was used. The statistical characteristics of the database are presented in Table 1.

Table 1: Statistical characteristics of the database

Material	No.	Parameters	Units	Mean	STD	COV (%)	Min.	Max.
Concrete	1	D_c	[mm]	154.00	47.13	31	51.00	406.00
	2	f'_c	[MPa]	52.1	29.4	57	16.6	188.2
FRP Jacket	3	t_f	[mm]	0.83	0.91	111	0.09	7.26
	4	E_f	[GPa]	178.53	117.66	66	10.50	662.50
	5	f_f	[MPa]	2710.1	1337.8	49	220.0	4441.0
	6	ε_f	[mm/mm]	0.01785	0.00698	39	0.00255	0.04690

Note: STD = standard deviation; COV = coefficient of variation; Min. = minimum; Max. = maximum; D_c = diameter of concrete columns; f'_c = unconfined concrete strength; t_f = thickness of FRP jacket; E_f = modulus of elasticity of FRP jacket; f_f = tensile strength of the FRP jacket; and ε_f = *rupture strain of FRP jacket*.

The bias and the coefficient of variation of the resistance can be estimated as the mean and the coefficient of variation of the measured over predicted values of the compressive strength. The predicted capacity was estimated using Eq.2 through Eq.4, suggested by ACI440.2-17 [1].

$$\phi P_n = \phi\xi[0.85 f'_{cc}(A_g - A_{st}) + f_y A_{st}] \tag{2}$$

$$f'_{cc} = f'_c + \psi 3.3 \kappa_a f_l \tag{3}$$

$$f_l = \frac{2E_f t_f \kappa_\varepsilon \varepsilon_{fu}}{D} \tag{4}$$

where:

A_g, A_{st}	= Gross concrete and longitudinal steel reinforcement areas [mm^2]
D	= Diameter of concrete column [mm]
E_f	= Modulus of elasticity of FRP jacket [MPa]
f'_{cc}, f'_c	= Confined and unconfined concrete strength [MPa]
f_y, f_l	= Yield strength of steel, and confining pressure of FRP jacket [MPa]
P_n	= Nominal axial compressive strength [N]
t_f	= Thickness of FRP jacket [mm]
ε_{fu}	= Rupture strain of FRP jacket [mm/mm]
κ_a	= Geometry efficiency factor (= 1 for circular sections) [-]
κ_ε	= Strain efficiency factor (= 0.55 for FRP jacket) [-]
ξ	= Aaccidental eccentricity limitation (= 0.8 or 0.85 for tie or spiral) [-]
ψ	= Additional reduction factor [-]

It should be noted that ξ in Eq.2 accounts for the effect of accidental eccentricity which is a code limitation. Therefore, the analysis was conducted by setting ξ equal to 1. The coefficient of variation and the mean values of the experimental to predicted capacity for the two cases of ψ=0.95 and ψ=1 are shown in Figure 1. The cumulative distribution function (CDF) for each case is presented in Figure 1.

Discussion and Conclusion

The analysis results are presented in Figure 2. As the ratio of Q_D/Q_L increases, ϕ decreases irrespective of the reliability index as shown in Figure 2(a). Therefore, ϕ corresponding to Q_D/Q_L of 4.0 was chosen as the minimum reduction factor corresponding to each reliability index, as presented in Figure 2(b). The analysis also showed that selecting ϕ values based on setting ψ =1 provides a better predicted load capacity of the columns, which leads to a lower resistance bias factor. The hatched area in Figure 2(b) shows the target reliability zone of ACI 440.2R-17 [1] that was used in calibrating ψ. The same range was adopted in this study to recommend design values for ϕ. The calibrated values of ϕ ranged between 0.73 to 0.64 accordingly. The range of values approximately matches the reduction factor given by ACI 318-14 [2], 0.65. The current reduction factor, 0.65, corresponds to target reliability indices of 3.42 and 3.48 using the experimental database for ψ =1, and ψ =0.95, respectively. Overall, the analysis showed that the current reduction factor, 0.65, gives a compatible target reliability index with what was used in calibrating the ACI standards.

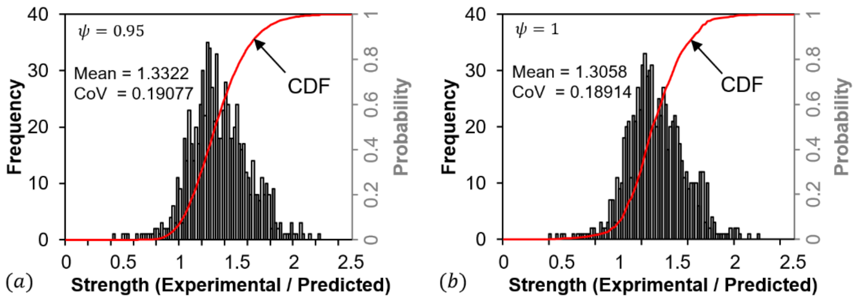

Figure 1: Normalized strength histograms: (a) ψ =0.95; and (b) ψ =1.

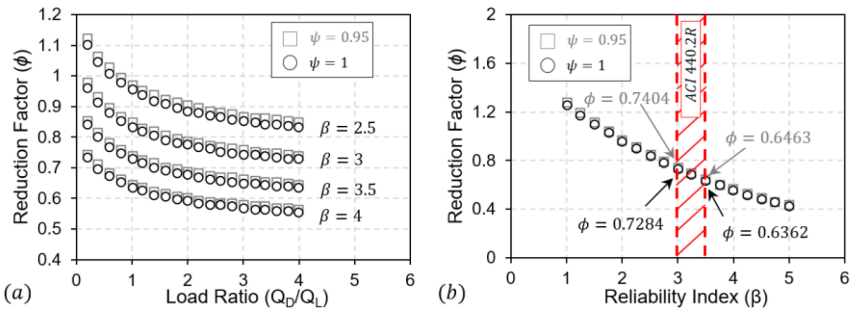

Figure 2: Resistance factor: (a) Load ratio versus resistance factor; and (b) reliability index versus resistance factor.

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