Design-oriented analysis of slender RC columns strengthened with longitudinal high modulus CFRP Laminates

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DESIGN-ORIENTED ANALYSIS OF SLENDER RC COLUMNS STRENGTHENED WITH LONGITUDINAL HIGH MODULUS CFRP LAMINATES

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ABSTRACT

This paper investigates the effectiveness of high modulus fiber reinforced polymer (FRP) composites for strengthening of slender reinforced concrete (RC) columns. Most research on strengthening RC columns using FRP composites has focused on the confinement issue of the concrete section; however slender RC columns may suffer overall buckling failure at loads much lower than their counterpart short columns. This paper is focused on using an analytical model based on modifying the provisions of ACI 318-08 to develop the loath path of the slender columns. Using the load paths and cross-sectional axial load-bending moment interaction curves, the interaction curves of the slender columns are developed. Moreover, through a parametric study, the effectiveness of CFRP laminates is evaluated for different slenderness ratios, CFRP reinforcement ratios, and effective length factors. It is shown that the longitudinal CFRP reinforcements are more effective on slender columns.

INTRODUCTION

As structures age, they experience an accumulation of deterioration and can also be required to accommodate an increase in loads. Therefore, the inconvenience of total replacement requires that a non-destructive, easily applied method of strengthening be utilized. Strengthening techniques using fiber reinforced polymers (FRP) have several advantages over conventional methods based on using steel and concrete. For example, FRP has high strength to weight and stiffness to weight ratios, non-corrosive properties, and are easy to install.

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Strengthening can be achieved in a concrete column by wrapping the column with FRP [1][2][3]. FRP systems can be used to increase the axial compression strength of a concrete member by providing confinement with an FRP jacket [4][5]. The concrete-filled FRP tubes (CFFT) technique has also been used successfully for different structures [6][7].

The research on slender concrete columns strengthened with FRP is still limited. Mirimiran et al. [7] started the research in this field with CFFT. They showed that as the slenderness ratio increased, the columns strength dropped rapidly. An investigation of slender reinforced concrete columns wrapped with FRP was conducted by Pan et al. [8]. Confinement with a unidirectional and also a bidirectional carbon FRP (CFRP) jacket was studied by Tao and Yu [9]. The study showed that the longitudinal fibers become more effective when bending becomes more predominant.

Fitzwilliam and Bisby [10] conducted small-scale tests where columns were wrapped with CFRP in a hoop and also in a longitudinal direction. The study showed that slender columns wrapped in a hoop direction showed only a slight increase in capacity compared to a longitudinal direction wrap where the behavior was much improved and higher strengths and capacities were achieved. Shaat and Fam [11] looked at the application of high modulus CFRP plates to strengthen slender steel columns. Nonetheless, research on the effectiveness of FRP plates to strengthen slender reinforced concrete columns is very limited. Recently, Sadeghian and Fam [12] demonstrated that longitudinal FRPs are very effective for the strengthening of slender reinforced concrete (RC) columns. The have developed an iterative second order analysis to predict the load path of the slender columns.

This paper addresses the effect of bonding longitudinal high CFRP laminates to the sides of a slender RC column, in order to enhance its flexural rigidity. This in turn enhances its buckling load according to Euler's buckling rule. Hence, the ultimate load for a slender column depends mainly on the flexural rigidity and load path rather than the axial rigidity. It is focused on using a design-oriented analytical model to evaluate the effectiveness of the laminates in strengthening slender RC columns with different slenderness ratios, CFRP reinforcement ratios, and effective length factors. The analytical model is based on modifying the provisions of ACI 318-08 [13] for flexural rigidity of slender RC columns without iterative second order analysis. The model also employs the computer software Response 2000 [14] to develop cross-sectional axial load-bending moment interaction curves to develop the interaction curves of the slender columns.

ANALYTICAL MODEL

This section introduces an analytical model that can be used to predict the performance of slender RC columns strengthened with longitudinal CFRP laminates. The model consists of two steps. The first part employs the computer software Response 2000 to determine the resistance of a short column represented by a cross-section interaction curve. In the second step, using the load path developed based on modifying the provisions of ACI 318-08, the interaction curve can be turned into a slender-column interaction curve to determine the resistance of a slender column without the additional second order effects.

Cross-Sectional Analysis

The cross-sectional load-moment interaction curve represents the capacity for the particular RC cross-section. To determine the interaction curve, this model employs the computer software Response 2000. The software allows analysis of beams subjected to arbitrary combinations of axial load, moment, and shear; and is based on the Modified Compression Field Theory by Vecchio and Collins [15]. Two assumptions implicit within Response 2000 is that plane sections remain plane, and that there is no transverse clamping stress across the depth of the beam [16]. Using Response 2000, the cross-section interaction curve can be outputted for any particular cross-section. Wherever the failure path intersects the interaction curve determines the axial load at which the column will fail. If the failure path turns horizontal before reaching the interaction curve, a stability failure occurs as shown in Figure 1(a).

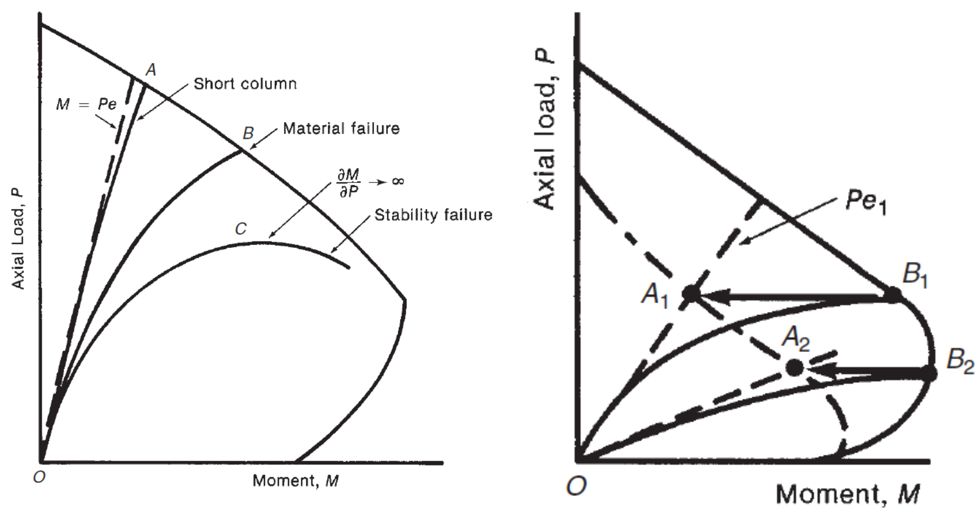

Figure 1. (a) Material and stability failures, and (b) slender column interaction curves. [17]

All column information such as cross-section, material data, and reinforcement details is inputted through a graphical interface. In the first step, the basic material properties are inputted and in later steps accurate material data can be inputted. Next, the geometry of the cross section, the number and type of longitudinal bars, and the type and spacing of transverse steel is selected. This creates the entire cross section and shows it graphically on the screen.

In order to obtain accurate analysis, proper material models are needed. For concrete, the program automatically assumes a stress-strain curve. The compression softening for normal strength concrete is modeled using the equation proposed by Vecchio and Collins [15] and tension stiffening using the equations proposed by Bentz [16]. The steel material properties are defined by the elastic modulus, yield strength, strain hardening, rupture strain, and ultimate strength. Response 2000 does not have FRP as an available material. Therefore, FRP must be simulated by inputting its properties as steel reinforcement. However, FRP does not yield like steel. Therefore, to properly simulate its behavior, the FRP's ultimate strength is inputted as both the yield and ultimate strength. The strain at break is inputted as the e-strain hardening and the rupture strain is inputted as a value that is twice as large as the e-strain hardening. This creates a fake stress-strain curve that Response 2000 will recognize. Therefore, when the software indicates the FRP has yielded, in actuality the FRP has ruptured. Using the software, the interaction curve can be solved.

Slender Column Load Path

To determine the load path of slender columns, the design provisions of ACI 318-08 provide an approach referred to as the "Moment Magnification Procedure" to account for the secondary effects. The method states that compression members shall be designed for factored axial force P_u and the factored moment amplified for the effects of member curvature M_c as

$$M_c = \delta_{ns} M_2 \quad (1)$$

where M_2 is the end moment, the moment magnifier δ_{ns} is taken as

$$\delta_{ns} = \frac{C_m}{1-\frac{P_u}{P_c}} \geq 1.0 \quad (2)$$

and the critical buckling load P_c is taken as

$$P_c = \frac{\pi^2 EI}{(kl_u)^2} \quad (3)$$

where l_u is the unsupported length and k is the effective length factor. The stiffness EI shall be taken as

$$EI = \frac{(0.2E_c I_g + E_s I_{se})}{1+\beta_{dns}} \quad (4)$$

where E_c and E_s are the modulus of elasticity of the concrete and steel, respectively, I_g is the gross moment of inertia, I_{se} is the moment of inertia of the steel, and β_{dns} is the ratio of the maximum factored axial dead load to the total factored axial load.

Contribution of FRP to Column Strength

In order to account for the FRP contribution, modifying Equation (5) to include the FRP stiffness is proposed, as shown in the following equation:

$$EI = \frac{(0.2E_c I_g + E_s I_{se} + E_f I_f)}{1+\beta_{dns}} \quad (5)$$

where E_f and If are the modulus of elasticity and moment of inertia of the FRP, respectively. Using these equations, the failure path on a moment interaction curve, as shown in Figure 1(a), for a particular column strengthened with FRP laminates can be determined.

Slender-Column Interaction Curve

To better discuss the effects of variables on slender column strength, it is convenient to turn the cross-section interaction curves into slender-column interaction curves. Line O-B_1 in Figure 1(b) shows the load-maximum moment curve for a column of given slenderness and end eccentricity and is determined using the above equations. As stated previously, the column fails when the failure path intersects the cross-section interaction curve at B_1. At the time of failure, the load and moment at the end of the column are given by point A_1. Therefore, if this process is repeated using the equations above and for different end eccentricities, we can get the FRP strengthened slender-column interaction curve. For the dimensions of the known column's cross-section, the material properties, slenderness, and end eccentricity, the axial load at which the slender column will fail can be determined.

Predicting Performance of Strengthened Slender Columns

The predicted performance of reinforced concrete columns of varying slenderness ratios strengthened with different amounts of ultrahigh modulus CFRP strips (400 GPa) were determined using the above procedures. Variables kept constant in this study included the cross-section dimensions of the column, internal longitudinal steel reinforcement, the transverse reinforcement, the concrete strength, and the eccentricity of the applied load. The cross-sections of the columns analyzed had a consistent height and width of 150mm and 300 mm, respectively. The longitudinal reinforcement consisted of four 15M steel rebar with clear concrete covers of 16 mm. The transverse reinforcement of each specimen included 5 mm diameter ties spaced at 150mm and 75mm.

The concrete strength was 50 MPa and the axial load was applied at an eccentricity of 19.5 mm, the minimum value according to the ACI 318-08. The parameters analyzed in this study included the slenderness ratio or column length, the FRP reinforcement ratio, and the effective length factor *k*. Table I summarizes the analysis matrix, parameters, and resulting maximum predicted axial loads and failure modes.

RESULTS AND DISCUSSIONS

The effect of the slenderness ratio on performance is shown in Figures 2 and 3. Figure 2 presents the slender-column interaction curves of strengthened columns of three different slender lengths (2000 mm, 3000 mm, and 4000 mm) and compares them to their unstrengthened curves. The strengthened columns in Figure 2 have FRP reinforcement ratios of 0.39%. Figure 3 presents the short-column interaction curve for strengthened columns of short length 990 mm. Figure 4 shows the variation of the percentage increase in axial strength with length or slenderness ratio. The figure shows increases of 7.7%, 19.6%, 32.1%, and 36.4 for columns with slenderness ratios of 22, 44, 67, and 89 (990 mm, 2000 mm, 3000 mm, and 4000 mm) respectively and FRP reinforcement ratios of 0.39%.

TABLE I. ANALYSIS MATRIX.

Set	Column	L (mm)	kL/r	ρ_f (%)	E_f (GPa)	k	Predicted P_{max} (kN)	Failure Mode
1-short	1-1	990	22	0	N/A	1	1685	CC*
	1-2			0.39	400	1	1815	CC
	1-3			0.77	400	1	1950	CC
	1-4			1.16	400	1	2085	CC
	1-5			1.54	400	1	2205	CC
								CC
2-slender	2-1	2000	44	0	N/A	1	1150	CC
	2-2			0.39	400	1	1375	CC
	2-3			0.77	400	1	1575	CC
	2-4			1.16	400	1	1750	CC
	2-5			1.54	400	1	1900	CC
3-slender	3-1	3000	67	0	N/A	1	700	TSY** → CC
	3-2		46.7	0	N/A	0.7	1010	CC
	3-3		33.5	0	N/A	0.5	1375	CC
	3-4		67	0.39	400	1	925	CC
	3-4		46.7	0.39	400	0.7	1250	CC
	3-5		33.5	0.39	400	0.5	1590	CC
	3-6		67	0.77	400	1	1115	CC
	3-7		67	1.16	400	1	1300	CC
	3-8		67	1.54	400	1	1475	CC
4-slender	4-1	4000	89	0	N/A	1	440	TSY → CC
	4-2			0.39	400	1	600	TSY → CC
	4-3			0.77	400	1	750	CC
	4-4			1.16	400	1	895	CC
	4-5			1.54	400	1	1036	CC

*CC: Concrete Crushing **TSY: Tension Steel Yields

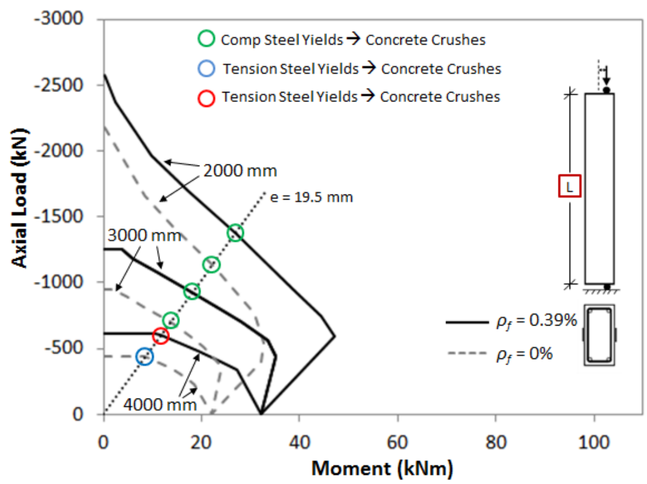

Figure 2. Slender-column interaction curves of strengthened columns.

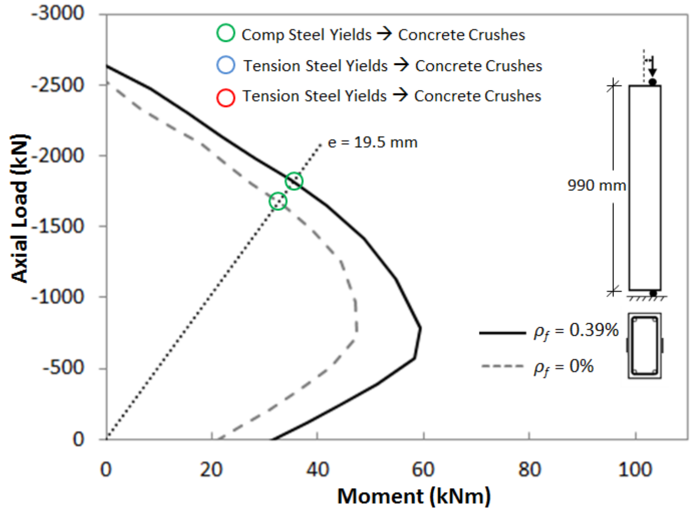

Figure 3. Short-column interaction curve for strengthened columns.

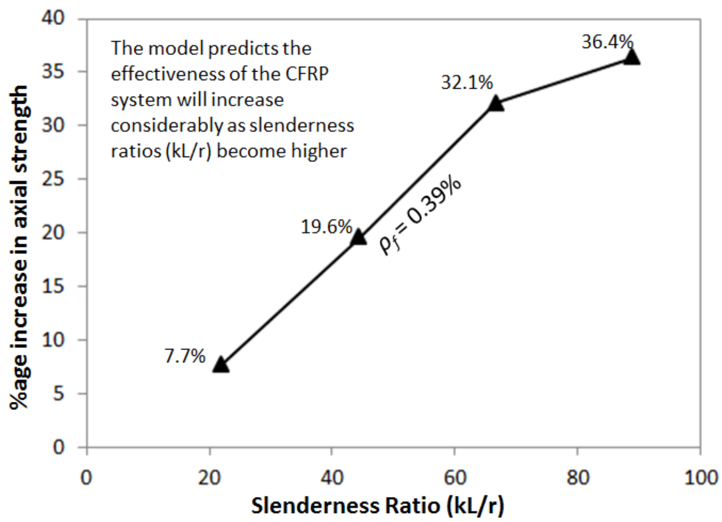

Figure 4. Variation of strength gain due to strengthening with slenderness ratio of column.

The effect of the FRP reinforcement ratio on performance is shown in Figure 5. Figure 5(a) presents the short-column interaction curve of strengthened short columns with four different FRP reinforcement ratios (0.39%, 0.77%, 1.16%, and 1.54%) all of length 990 mm. Figure 5(b-d) present the slender-column interaction curves of strengthened slender columns with four different FRP reinforcement ratios (0.39%, 0.77%, 1.16%, and 1.54%) and three different column lengths (2000 mm, 3000 mm, and 4000 mm). It also indicates that in the longer slender column curves (3000 mm and 4000 mm) there is a critical point where the column reaches its buckling load and its failure mode changes from a material to stability failure. Therefore, for smaller loading eccentricities the maximum axial load will be limited.

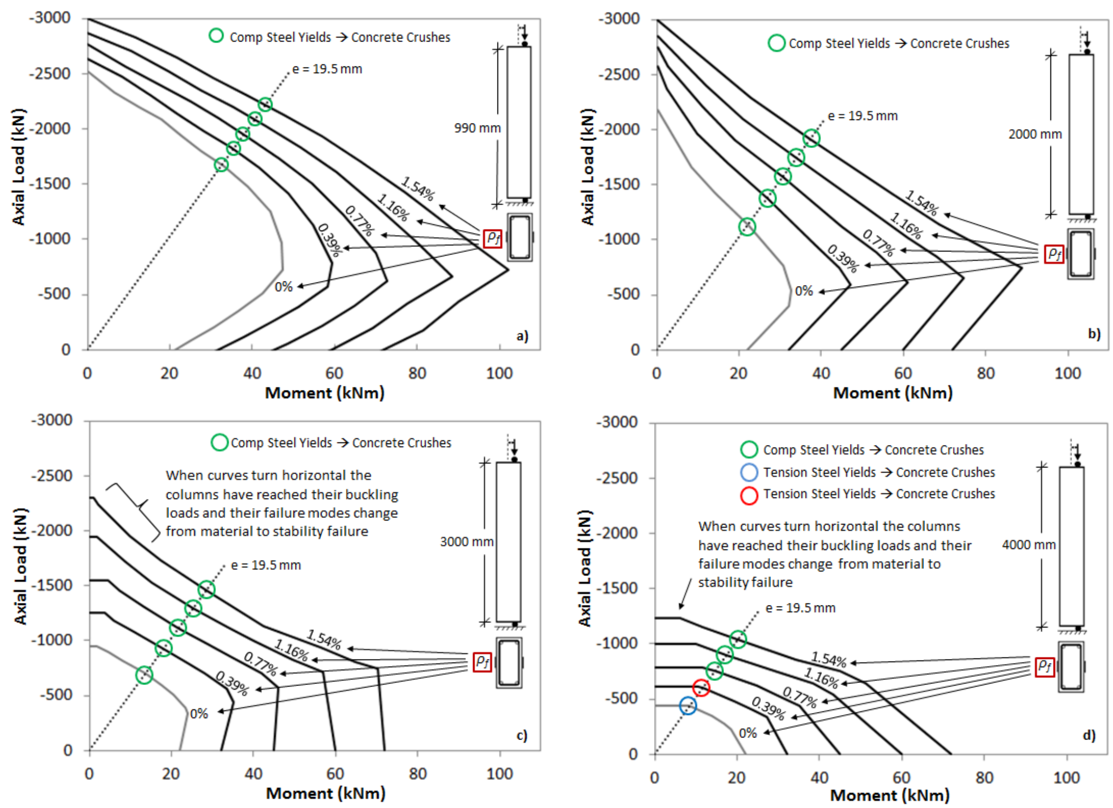

Figure 5. Effect of FRP reinforcement ratio and slenderness on slender-column interaction curves: (a) L=990 mm; (b) L=2000 mm; (b) L=3000 mm; and (b) L=4000 mm.

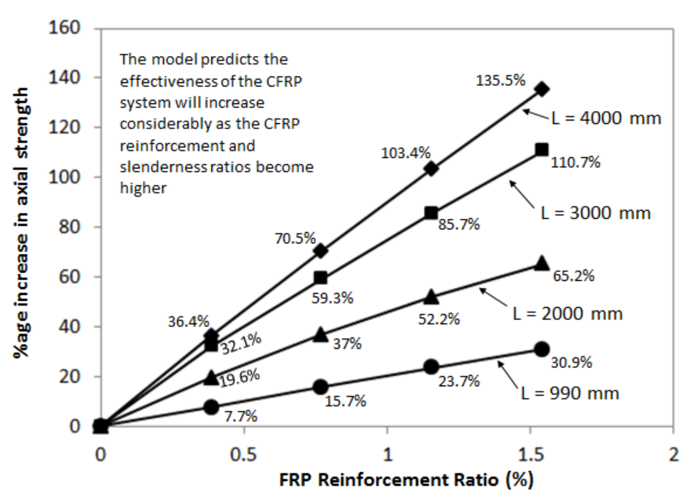

Figure 6. Variation of strength gain due to strengthening with FRP reinforcement ratio and length of column.

Figure 6 shows the variation of the percentage increase in axial strength with FRP reinforcement ratio. As expected, the model predicts the effectiveness of the FRP strengthening system increases as the FRP reinforcement ratio increases. In addition, the figure shows that the FRP strengthening system has a much greater effect on the slender columns (2000 mm, 3000 mm, and 4000 mm) as opposed to the short column (990 mm).

The effect of the effective length factor k on performance is shown in Figure 7. The figure presents the slender-column interaction curves of strengthened slender columns with three different effective length factors (0.5, 0.7, and 1.0) and compares them to their unstrengthened curves.

Figure 8 shows the variation of the percentage increase in axial strength with the effective length factor. The figure shows increases of 15.6%, 22.2%, and 32.1% for k values of 0.5, 0.7, and 1.0, respectively, and FRP reinforcement ratios of 0.39%.

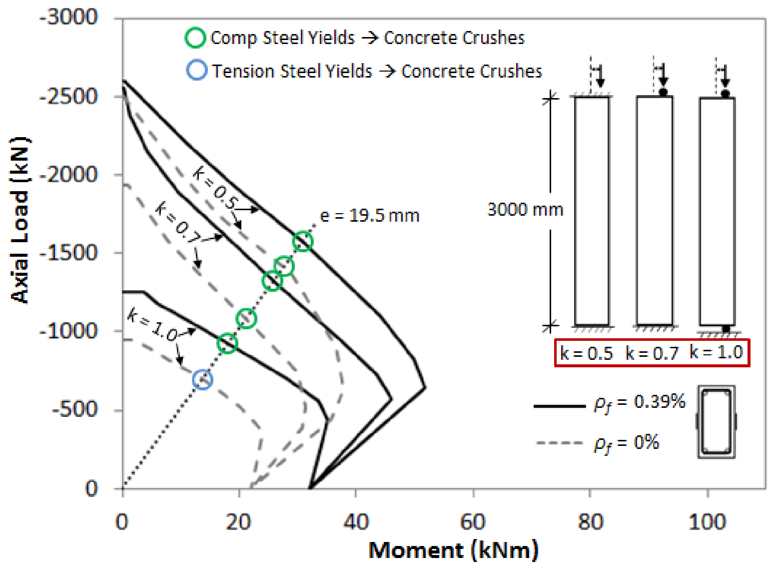

Figure 7. Effect of effective length factor k on slender-column interaction curves.

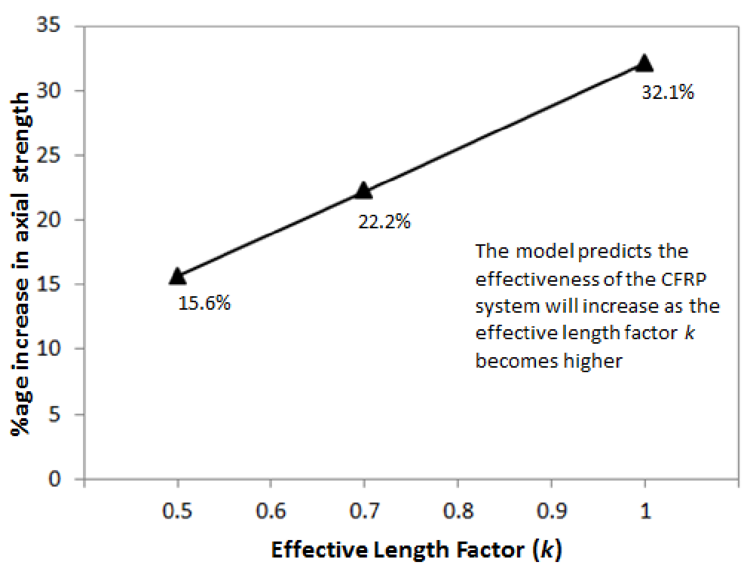

Figure 8. Variation of strength gain due to strengthening with effective length factor k.

CONCLUSIONS

In this paper, an analytical model was developed to predict the behavior and load path of slender RC columns strengthened with longitudinal high modulus CFRP reinforcements. The analytical model was based on modifying the provisions of ACI 318-08 to evaluate the effectiveness of ultrahigh modulus CFRP laminates in strengthening slender RC columns in two steps. The first step employed the computer software Response 2000 to determine the resistance of a short column represented by a cross-section interaction curve. In the second step, the curve was turned into a slender-column interaction curve using load paths of slender columns to determine the resistance of a slender column without the additional second order effects. To determine the load paths, the design provision of ACI 318-08 was modified through adding a new term for FRPs into flexural rigidity EI of columns. A parametric study was performed with different slenderness ratios, CFRP reinforcement ratios, and effective length factors. It was shown that the effectiveness of the FRP strengthening system increases as the FRP reinforcement ratio increases. In addition, the FRP strengthening system has a much greater effect on the slender columns as opposed to the short column. It also found that in longer slender column curves there is a critical point where the column reaches its buckling load and its failure mode changes from a material to stability failure. Therefore, for smaller loading eccentricities the maximum axial load will be limited.

REFERENCES

1. Lee, C., Bonacci, J.F., Thomas, M.D.A., Maalej, M., Khajehpour,S., Hearn, N., Pantazopoulou, S., and Sheikh, S. 2000. "Accelerated Corrosion and Repair of Reinforced Concrete Columns using Carbon Fibre Reinforced Polymer Sheets." *Canadian Journal of Civil Engineering*, 27:941-948.
2. Pantazopoulou, S.J., Bonacci, J.F., Sheikh, S., Thomas, M.D.A., and Hearn, N. 2001. "Repair of Corrosion-Damaged Columns with FRP Wraps." *Journal of Composites for Construction*, ASCE, 5(1):3-11.
3. Masoud, S., and Soudki, K.A. 2002. "Post-repair Performance of Corroded Reinforced Concrete Beams Repaired with FRP Sheets." Proceedings of the 2nd International Conference on Durability of Fiber Reinforced Polymer Composites for Construction, Montréal, Que., 29–31 May 2002. *Edited by* B. Benmokrane and E. El-Salakawy. Université de Sherbrooke, Quebec, Canada, pp. 113-126.
4. Nanni, A., and Bradford, N. 1995. "FRP Jacketed Concrete under Uniaxial Compression." *Construction and Building Materials*, 9(2):115-124.
5. Toutanji, H. 1999. "Stress-Strain Characteristics of Concrete Columns Externally Confined with Advanced Fiber Composite Sheets." *ACI Materials Journal*, 96(3):397-404.
6. Fam, A., and Rizkalla, S. H. 2001. "Behavior of Axially Loaded Concrete-Filled Circular Fiber-Reinforced Polymer Tubes." *ACI Structural Journal*, 98(3):280–289.
7. Mirmiran, A., Shahawy, M., Beitleman, T. 2001. "Slenderness Limit for Hybrid FRP–Concrete Columns." *Journal of Composites for Construction*, 5(1):26-34.
8. Pan, J. L., Xu, T., Hu, Z. J. 2007. "Experimental Investigation of Load Carrying Capacity of the Slender Reinforced Concrete Column Wrapped with FRP." *Construction and Building Materials*, 21(11):1991-1996.
9. Tao, Z and Yu, Q. 2008. "Behaviour of CFRP-Strengthened Slender Square RC Columns." *Magazine of Concrete Research 2008*, 60(7):523-533.
10. Fitzwilliam, J. and Bisby, L.A. 2010. "Slenderness Effects on Circular CFRP-Confined Reinforced Concrete Columns." *Journal of Composites for Construction,* ASCE, 14(3):280-288.

11. Shaat, A. and Fam, A. 2009. “Slender Steel Columns Strengthened using High-Modulus CFRP Plates for Buckling Control.” *Journal of Composites for Construction*, ASCE, 13(1):2-12.
12. Sadeghian, P. and Fam, A. 2013. “Strengthening Slender Reinforced Concrete Columns using Bonded CFRP Laminates.” *Proceedings of the 11th International Symposium on Fiber-Reinforced Polymers Reinforcement for Concrete Structures* (*FRPRCS-11)*, 26-28 June 2013. *Edited by* J. Barros, University of Minho, Guimarães, Portugal.
13. ACI Committee 318. 2008. “Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (318R-08).” Farmington Hills: American Concrete Institute.
14. Bentz, E. C., and Collins, M. P. 2000. “Response 2000 Software Program for Load-Deformation Response of Reinforced Concrete Section.” http://www.ecf.utoronto.ca/~bentz/r2k.htm.
15. Vecchio, F. J., and Collins, M. P. 1986. “The modified compression-field theory for reinforced concrete elements subjected to shear.” ACI J., 83(2):219-231.
16. Bentz, E.C. 2000. “Sectional Analysis of Reinforced Concrete Members.” PhD Thesis, Department of Civil Engineering, University of Toronto, 310 pp.
17. Wight, J. and MacGregor, J. 2012. *Reinforced Concrete Mechanics and Design: Sixth Edition*, Pearson Education Inc., Upper Saddle River, New Jersey.