Slender reinforced concrete columns strengthened with longitudinal FRP reinforcements

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2 authors:

Pedram Sadeghian
Dalhousie University

Amir Fam
Queen's University

SLENDER REINFORCED CONCRETE COLUMNS STRENGTHENED WITH LONGITUDINAL FRP REINFORCEMENTS

Pedram SADEGHIAN
Assistant Professor of Civil Engineering, The Pennsylvania State University at Harrisburg, USA
pedram@psu.edu

Amir FAM
Professor, Donald and Sarah Munro Chair in Engineering and Applied Science, Queen's University, Canada
fam@civil.queensu.ca

ABSTRACT: This paper studies the effects of longitudinal fiber reinforced polymer (FRP) reinforcements bonded to the sides of slender reinforced concrete (RC) columns, in order to enhance flexural rigidity of the columns. As the ultimate load for a slender column depends mainly on flexural rigidity rather than axial rigidity, longitudinal high modulus FRPs can reduce lateral deformations and corresponding second-order moments of the column. This in turn enhances buckling load of the column through reducing P-delta effect and changing load path of the slender column. The longitudinal strengthening system can also change failure mode of the slender columns from buckling failure to material failure, which is more desirable. This study employs an analytical procedure based on ACI 318 formulas and moment magnification procedure for conventional slender RC columns. A parametric study is performed to build a data bank of theoretical flexural stiffness towards calculation of flexural stiffness used by ACI 318. In conclusion, a formula similar to that of conventional slender RC columns in ACI-318 is recommended, however more research with larger data bank is needed to propose a reliable formula for design.

1. Introduction

In the past two decades, strengthening of existing reinforced concrete (RC) columns with externally bonded fiber reinforced polymer (FRP) composites has been researched by many researchers. It has commonly been accepted that applying transverse FRPs (i.e. FRP wraps) on RC columns can effectively provide lateral confinement on concrete core and enhance strength and ductility of the columns under concentric compressive loadings. Transverse FRPs has also been successfully examined for strengthening of RC columns under eccentric compressive loadings. It is now widely accepted that transverse FRPs can enlarge axial load-bending moment (P-M) interaction curves of RC columns under combination of large axial loads and low bending moments. Recently, Fitzwilliam and Bisby (2010), Jiang and Teng (2012) have studied strengthening of slender RC columns with transverse FRPs, where their concentrations have been on enlarging P-M interaction curves and enhancing of the performance of the columns through confinement. However, Fitzwilliam and Bisby (2010) have demonstrated the effectiveness of longitudinal FRPs to reduce lateral deflections and allow slender columns to achieve higher strengths. As the performance of slender RC columns strengthened with FRPs is not well known, there is a gap in design guidelines such as ACI 440.2R (2008).

The effect of longitudinal FRPs on slender RC columns has been neglected based on the lower stiffness of conventional FRPs in comparison to steel reinforcements, which is very important parameter for second-order deformations. However, these days, based on the availability of some high modulus carbon FRPs (CFRPs) with elastic modulus up to two times of steel reinforcements, the effect of FRPs on second-order deformations can be completely different. Recently, Sadeghian and Fam (2014) have demonstrated that longitudinal FRPs such longitudinal fabrics, bonded laminates, and near surface mounted (NSM) systems are very effective for the strengthening of slender RC columns. They have developed an iterative second-order analysis to predict the load path of the slender columns. The model accounts for material and geometric nonlinearity as well as concrete cracking. The key feature of the model is that it achieves strengthening primarily by altering the load path of the column, through controlling second-order deflections, such that it intercepts the P-M interaction curve at a higher load. This is different from traditional strengthening approaches of RC columns, which aim primarily to enlarging the P-M interaction curve, rather than altering the loading path.

While FRP strengthening of short RC columns through applying confinement on concrete have been studied extensively, few studies as mentioned have been conducted on slender RC columns. Moreover, these few studies have been concentrated on strengthening through applying transverse FRPs and increasing confinement to enlarge P-M interaction curve and there is no study to concentrate on changing loading path through applying longitudinal FRPs and increasing flexural stiffness. This paper addresses the flexural stiffness of slender RC column strengthened with high-modulus bonded longitudinal FRPs through a design-oriented analytical model, not an iterative second-order analysis as developed by Sadeghian and Fam (2014). The model is based on modifying the provisions of ACI 318 (2011) for flexural stiffness of conventional slender RC columns. It is focused on using the design-oriented analytical model to evaluate the effectiveness of the FRPs in strengthening slender RC columns with different slenderness ratios, FRP reinforcement ratios, FRP modulus, and initial eccentricity ratio.

2. ANALYTICAL MODEL

This section introduces a design-oriented analytical model that can be used to predict the performance of slender RC columns strengthened with longitudinal FRPs. The model is based on modifying the provisions of ACI 318 for flexural stiffness of conventional slender RC columns that is called "moment magnification procedure".

2.1. Strengthening of Short and Slender RC Columns

Figure 1 shows performance of a short and slender RC column before and after strengthening with longitudinal high modulus FRPs. Straight line OA represents loading path related to a typical short RC column under compressive axial load P and eccentricity e_o. Applying longitudinal FRPs on this columns changes failure point A to A' which upgrades load capacity of the columns a little as shown in the figure. Let's consider a column with similar cross section, eccentricity, and strengthening system, but with larger length (i.e. a slender column). Because the column is slender, lateral deformations are significant and eccentricity at mid height increases extensively based on the concept of second-order deformations, which leads to typical non-linear loading path OB with a significant lower load capacity (i.e. failure point B) in compare to the short RC column (i.e. failure point A). It is expected to change load path OB to OB' by applying high modulus FRPs in order to upgrade failure point B to B' which represent a significant strengthening gain for slender column in compare to short column. This hypothesis is logical as second-order deformations are directly related to flexural stiffness of the slender column and high modulus FRPs are able to provide enough flexural stiffness to change the loading path. The authors believe that strengthening mechanism with longitudinal FRPs is fundamentally different to that of short and slender RC columns. For Short columns, strengthening gain attains only through enlarging interaction diagram, however for slender columns longitudinal high modulus FRPs are able to change loading path to achieve a significant strengthening gain as shown in Fig. 1(a).

2.2. Moment Magnification Procedure

Based on ACI 318-11, moment magnification procedure is an approximate design procedure that uses the moment magnifier concept to account for slenderness effects. Moments computed using an ordinary first-order frame analysis are multiplied by a moment magnifier that is a function of the axial load P and the critical buckling load P_c for the column. A first-order frame analysis is an elastic analysis that does not include the internal force effects resulting from deflections. For a non-sway column with single curvature and equal initial eccentricity e_o at both ends, first-order moment $M_o=P.e_o$ is amplified as the following:

$$M = \delta . M_o \quad (1)$$

where the moment magnifier δ and the critical buckling load P_c are taken as:

$$\delta = \frac{1}{1 - P/P_c} \quad (2)$$

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

where l is the unsupported length and k is the effective length factor. For conventional RC columns under short term loads, the stiffness parameter EI is taken as one of the following equations:

$$EI = 0.2E_c I_g + E_s I_{se} \tag{4}$$

$$EI = 0.4E_c I_g \tag{5}$$

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. Either Eq. (4) or (5) may be used to compute EI. Equation (4) was derived for small eccentricity ratios and high levels of axial load where slenderness effects are most pronounced. Eq. (5) is a simplified approximation to Eq. (4) and is less accurate (Mirza 1990).

In defining the critical load, the main problem is applying the moment magnifier concept to an inelastic, non-homogeneous material such as reinforced concrete is the manner in which the critical load of the column is defined. In particular, it is difficult to choose a value of the flexural stiffness EI which will reasonably approximate the variations in stiffness due to cracking, creep, and the nonlinearity of the concrete stress-strain curve (MacGregor et al. 1970 and Mirza 1990). The focus of this paper is on the flexural stiffness EI for slender RC columns strengthened with longitudinal FRPs that is discussed in the following section.

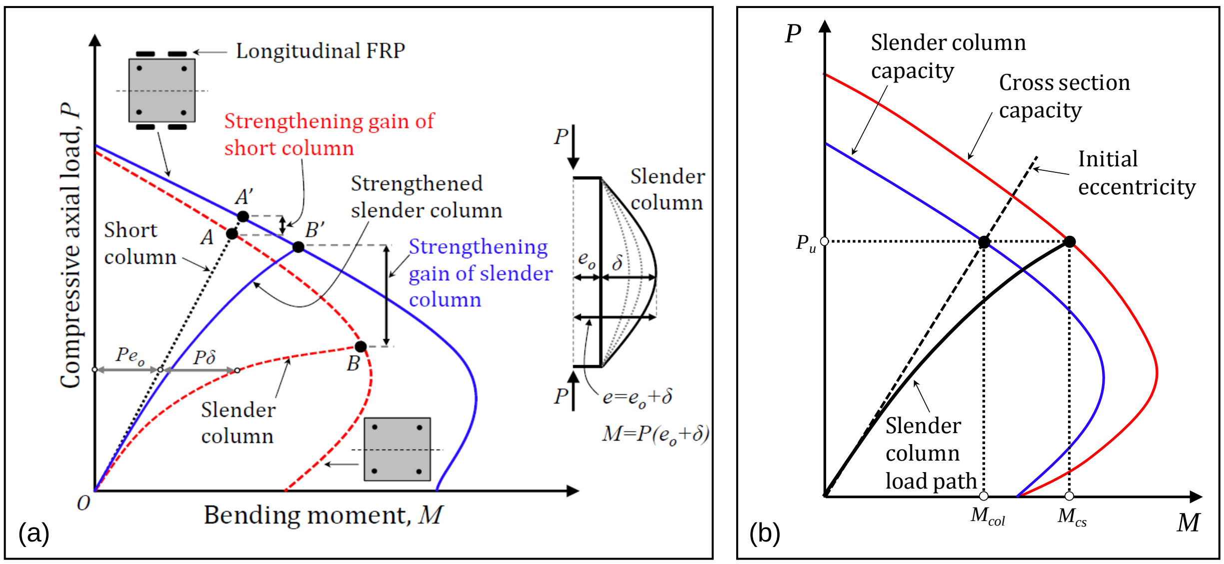

Fig. 1 – (a) Performance of short and slender RC columns before and after strengthening with longitudinal FRPs; (b) relationship between cross section capacity and slender column capacity.

2.3. Proposed Model

As mentioned, the flexural stiffness EI depends on cracking level and nonlinear behavior of the RC column. As longitudinal FRPs can change the behavior of a slender RC column, it is expected to see this difference as additional term for FRP contribution and possibly different coefficient for contribution of concrete. In order to account for the differences, modifying Eq. (4) is proposed to include effects of longitudinal FRPs, as shown in the following:

$$EI = \alpha E_c I_g + E_s I_{se} + E_f I_{fe} \tag{6}$$

where E_f and I_{fe} are the modulus of elasticity and moment of inertia of the FRP, respectively. The contribution of longitudinal FRPs is considered with the same format of the contribution longitudinal steel rebars. The dimensionless coefficient α is considered as a general form of a reduction factor which depends on the cracking level and stiffness of slender RC column strengthened with longitudinal FRPs. The coefficient α can be expressed as the following:

$$\alpha = \left(EI - E_s I_{se} - E_f I_{fe}\right) / E_c I_g \quad (7)$$

The procedure describing in the following is adopted from Mirza (1990) for conventional slender RC columns. The second-order moment of a pin-pin slender column subjected to equal and opposite end moments is given by Timoshenko and Gere (1961) as the following (secant formula):

$$M = M_o \sec\left(\frac{\pi}{2}\sqrt{\frac{P_u}{P_c}}\right) \quad (8)$$

where M is design bending moment which includes second-order effects; M_o is applied end moment calculated by a conventional elastic frame analysis; P_u is factored axial load acting on the column; and P_c is Euler's buckling strength (Eq. 3). For the purpose of current analysis, M and M_o are respectively replaced by the cross-sectional bending moment capacity M_{cs} and the overall column bending moment capacity M_{col} (as shown in Fig. 1b). Thus, Eq. (8) can be rearranged as the below:

$$P_c = \frac{\pi^2 P_u}{4\left[\sec^{-1}\left(M_{cs} / M_{col}\right)\right]^2} \quad (9)$$

Substituting Euler's buckling strength (Eq. 3) for a pin-pin column (k=1) in Eq. (9) and solving it for EI gives the following expression:

$$EI = \frac{P_u l^2}{4\left[\sec^{-1}\left(M_{cs} / M_{col}\right)\right]^2} \quad (10)$$

Eq. (10) is the theoretical flexural stiffness of a pin-pin slender column subjected to single curvature bending with equal moments acting at both ends. The terms M_{cs} and M_{col} used in this expression is computed based on a procedure developed by the authors (Sadeghian and Fam 2013) for the load path of slender RC columns strengthened by longitudinal FRPs.

2.4. Parametric Study

The iterative model (Sadeghian and Fam 2014) is applied to investigate the effects of key parameters on behavior of slender RC columns strengthened with longitudinal FRP reinforcement, including slenderness ratio (λ=kl/r); FRP reinforcement ratio (ρ_f); FRP modulus (E_f), and initial eccentricity ratio (e_o/h). As shown in Table 1, for a total of 41 cases, the range of values are λ=40, 60, 80, 100, and 120; ρ_f=0, 0.1, 0.3, 0.5, and 0.7%; E_f=100, 200, 300, 400, and 500 GPa; and e_o/h=0.01, 0.05, 0.1. 0.2, 0.3, 0.6, and 1. The rest of parameters, namely cross-section b=h=400 mm, FRP tensile strength f_{fu}=1500 MPa, concrete strength f'_c=40 MPa, steel yielding strength f_y=400 MPa, steel modulus E_s=200 GPa, and steel reinforcement ratio ρ_s=2% are kept constant.

For each case, M_{cs}, P_u, M_{col} and pure axial capacity of cross-section P_o are calculated using the iterative model, interaction diagrams, and procedure explained in this paper. Then the theoretical flexural stiffness EI and coefficient α are calculated using Eq. (10) and Eq. (8), respectively. Fig. 2(a) and 2(b) show variation of coefficient α versus eccentricity ratio and load capacity ratio, respectively. Fig. 2(a) shows that the variation of coefficient α for small initial eccentricities is more than large initial eccentricities. Moreover, when initial eccentricities increases, coefficient α decreases to slightly below 0.2. Fig. 2(b) shows that coefficient α for small load capacity ratios is slightly less than 0.2. When load capacity ratio increases, coefficient α increases to a peak of slightly less than 0.6 and then decreases. In general a lower limit about α=0.2 similar to ACI 318 seems appropriate for design applications. Fig. 3(a) shows the ratio of the theoretical flexural stiffness EI over flexural stiffness EI calculated with α=0.2. It shoes that the lower limit is slightly less than 1 and upper limit is slightly less than 2. It means α=0.2 might be an appropriate number for design application; however more research with larger data bank is needed to propose a reliable coefficient. Using the coefficient α=0.2, the load path of a column tested by Gajdosova and Bilcik (2013) is calculated and shown in Fig. 3(b). The iterative second-order analysis results developed by Sadeghian and Fam (2014) is also presented, where it shows a good agreement. The possibility of a failure controlled by FRP debonding under compression should also be studied further.

Table 1 – Summary of parametric study for theoretical stiffness data.

Case #	λ	ρ_f (%)	E_f (GPa)	e_o/h	P_o (kN)	M_{cs} (kN-m)	P_u(kN)	M_{col} (kN-m)	EI (kN-m^2)	α	P_u/P_o	$EI_{\alpha=0.2}$ (kN-m^2)	$EI / EI_{\alpha=0.2}$
1	40	0	400	0.1	7550	298	5075	203.0	43360	0.535	0.672	22111	1.96
2	60	0	400	0.1	7550	384	3836	153.4	36992	0.435	0.508	22111	1.67
3	80	0	400	0.1	7550	416	2686	107.4	36074	0.420	0.356	22111	1.63
4	100	0	400	0.1	7550	363	1815	72.6	34841	0.401	0.240	22111	1.58
5	120	0	400	0.1	7550	326	1124	45.0	28397	0.299	0.149	22111	1.28
6	40	0.5	400	0.1	8370	353	5980	239.2	50414	0.443	0.714	35001	1.44
7	60	0.5	400	0.1	8370	441	5123	204.9	56188	0.534	0.612	35001	1.61
8	80	0.5	400	0.1	8370	538	3845	153.8	53982	0.499	0.459	35001	1.54
9	100	0.5	400	0.1	8370	600	2564	102.6	47160	0.392	0.306	35001	1.35
10	120	0.5	400	0.1	8370	600	1714	68.6	41898	0.309	0.205	35001	1.20
11	40	1	400	0.1	9266	403	6870	274.8	58764	0.371	0.741	47891	1.23
12	60	1	400	0.1	9266	507	5990	239.6	66670	0.496	0.646	47891	1.39
13	80	1	400	0.1	9266	619	4758	190.3	69267	0.537	0.513	47891	1.45
14	100	1	400	0.1	9266	735	3404	136.2	63927	0.453	0.367	47891	1.33
15	120	1	400	0.1	9266	804	2400	96.0	59085	0.377	0.259	47891	1.23
16	60	0.5	400	0.01	8370	288	6532	26.1	38654	0.258	0.780	35001	1.10
17	60	0.5	400	0.05	8370	359	5977	119.5	51121	0.454	0.714	35001	1.46
18	60	0.5	400	0.2	8370	540	3830	306.4	53019	0.484	0.458	35001	1.51
19	60	0.5	400	0.3	8370	580	3010	361.2	48340	0.410	0.360	35001	1.38
20	60	0.5	400	0.6	8370	594	1800	432.0	40798	0.291	0.215	35001	1.17
21	60	0.1	400	0.1	7741	379	4405	176.2	48313	0.573	0.569	24689	1.96
22	60	0.3	400	0.1	8049	413	4746	189.8	51481	0.541	0.590	29845	1.72
23	60	0.7	400	0.1	8710	471	5485	219.4	60186	0.516	0.630	40157	1.50
24	100	0.1	400	0.1	7741	433	1843	73.7	33863	0.345	0.238	24689	1.37
25	100	0.3	400	0.1	8049	537	2191	87.6	39855	0.358	0.272	29845	1.34
26	100	0.7	400	0.1	8710	660	2933	117.3	54487	0.426	0.337	40157	1.36
27	60	0.5	100	0.1	7785	386	4437	177.5	48129	0.559	0.570	25334	1.90
28	60	0.5	200	0.1	7983	406	4661	186.4	50559	0.547	0.584	28556	1.77
29	60	0.5	300	0.1	8125	425	4888	195.5	53021	0.535	0.602	31779	1.67
30	60	0.5	500	0.1	8551	458	5355	214.2	59087	0.529	0.626	38224	1.55
31	120	0.5	400	0.3	8551	553	1229	147.5	37649	0.242	0.144	38224	0.98
32	100	0.5	400	0.3	8551	598	1638	196.6	38612	0.257	0.192	38224	1.01
33	80	0.5	400	0.3	8551	615	2278	273.4	42580	0.320	0.266	38224	1.11
34	60	0.5	400	0.3	8551	581	2980	357.6	46852	0.387	0.348	38224	1.23
35	40	0.5	400	0.3	8551	548	3627	435.2	49102	0.422	0.424	38224	1.28
32	120	0.5	400	0.6	8551	514	910	218.4	36809	0.229	0.106	38224	0.96
33	100	0.5	400	0.6	8551	540	1136	272.6	37730	0.243	0.133	38224	0.99
34	80	0.5	400	0.6	8551	574	1434	344.2	38423	0.254	0.168	38224	1.01
35	60	0.5	400	0.6	8551	613	1818	436.3	38904	0.262	0.213	38224	1.02
36	40	0.5	400	0.6	8551	621	2195	526.8	40535	0.287	0.257	38224	1.06
37	120	0.5	400	1	8551	485	669	267.6	35646	0.210	0.078	38224	0.93
38	100	0.5	400	1	8551	496	788	315.2	36393	0.222	0.092	38224	0.95
39	80	0.5	400	1	8551	518	934	373.6	36679	0.226	0.109	38224	0.96
40	60	0.5	400	1	8551	534	1090	436.0	37255	0.236	0.127	38224	0.97
41	40	0.5	400	1	8551	554	1254	501.6	37399	0.238	0.147	38224	0.98

3. Conclusion

In this paper, an analytical procedure was used to predict the flexural stiffness of slender RC columns strengthened with longitudinal FRP reinforcements. The analytical procedure was based on modifying the provisions of ACI 318 to evaluate the effectiveness of longitudinal FRP reinforcements. To determine the load paths of slender columns an iterative analytical model was used to find load and moment capacity of the slender columns. A parametric study was performed with different slenderness ratios, FRP reinforcement ratios, FRP modulus, and initial eccentricity ratio to prepare a data bank of flexural stiffness and coefficient α. It was shown that coefficient α is variable and it is a function of initial eccentricity and load capacity ratios. In general a lower limit with the value of about α=0.2 similar to ACI 318 seems appropriate for design of slender RC columns strengthened with longitudinal FRP reinforcements, however more research with larger data bank and considering FRP debonding under compression is needed to propose a reliable coefficient.

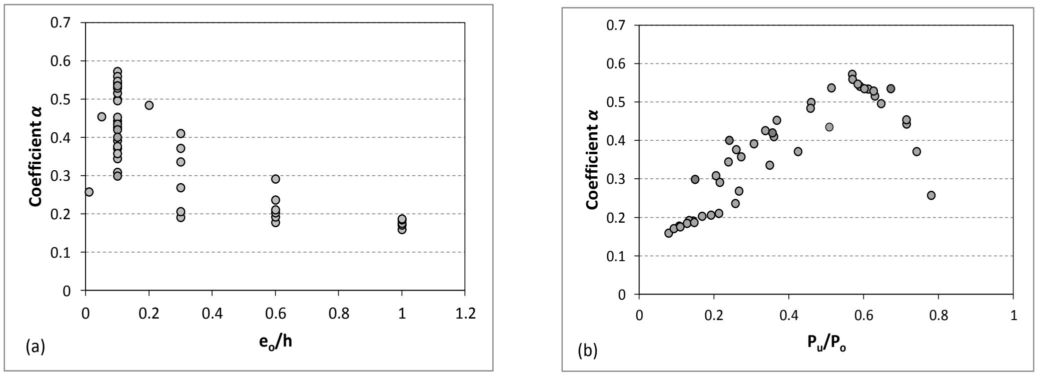

Fig. 2 – Variation of coefficient α versus (a) eccentricity ratio; (b) load capacity ratio.

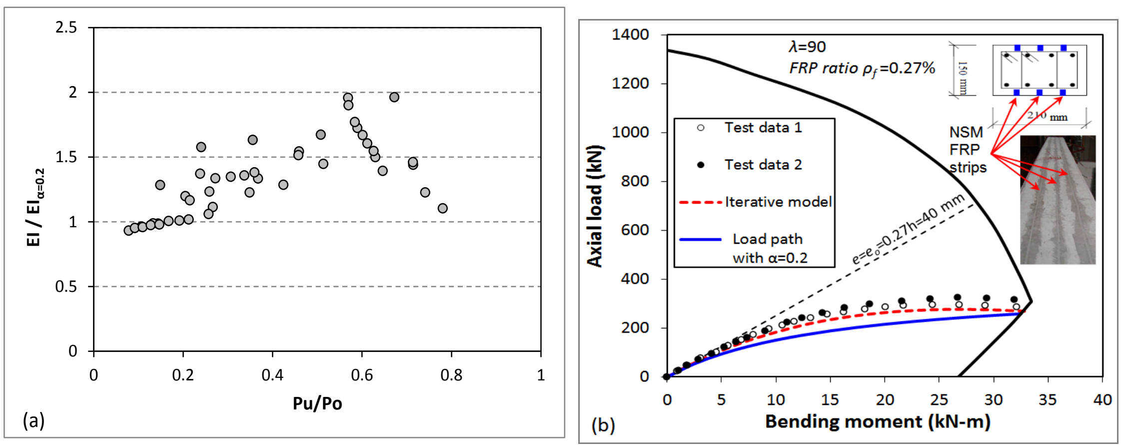

Fig. 3 – (a) Variation of *EI* / *EI*$_{\alpha=0.2}$ versus load capacity ratio; (b) comparison of load path with α=0.2 with experiment (Gajdosova and Bilcik 2013) and iterative model (Sadeghian and Fam 2014).

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