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Proposed Slenderness Limit for FRP Circular Concrete Column

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External bonding of circumferential fibre reinforced polymer (FRP) is a widely accepted technique to strengthen concrete structural component over the past decades. It is shown that FRP wraps increase the strength and deformability of structural components. Extensive studies have been performed on short RC columns with or without longitudinal rebar possessing length to diameter ratio less than three under concentric axial load to evaluate FRP effectiveness in these important structural elements. However, it should be noted that most of the practical RC columns have length to diameter ratio larger than three and are subjected to eccentric loading. Therefore, slenderness and axial load eccentricity are two decisive parameters which their effects on RC columns must be investigated.

Increase in slenderness and/or axial load eccentricity decreases the effectiveness of FRP confinement on improving strength and ductility of RC columns. Thus, it is crucial to specify a slenderness limit for FRP confined RC columns that ensure FRP wraps would be activated efficiently like how they work for short columns. This paper investigates the effects of slenderness and eccentricity of axial load on the strength of FRP confined RC columns and a relation for calculating slenderness limit of FRP wrapped circular RC columns is proposed based on numerical evaluations.

1. Introduction

Using FRP for strengthening concrete structures is one of the remarkable topics in civil engineering investigations. Nowadays, FRPs are widely used in structural applications due to their positive characteristics such as high strength, corrosion resistance, durability, ease of application and electromagnetic neutrality. Many studies are performed about the effects of FRP on concrete structures. In this field of investigations, many efforts are devoted to study FRP wrapped columns. Using FRPs for column confinement leads to increase in strength and ductility of concrete. However, it must be noticed that FRP effect on strength and ductility of concrete is negligible in slender columns. Because slenderness is a relative characteristic, there should be a limit to judge whether FRP confinement is efficient or not. Although FRPs are widely used for concrete columns strengthening, there are still major difficulties for designers. This is because relevant design provisions in the widely used design guidelines for FRP-strengthened RC structures [International Federation for Structural Concrete (FIB) 2001; ISIS Canada 2001; American Concrete Institute (ACI) 2002, 2008b; National Research Council (CNR) 2004; Concrete Society 2004] are restricted to the design of FRP jackets for short columns in which the slenderness (i.e., second-order) effect is negligible and none of them includes any information on the design of FRP jackets for slender columns.

Nevertheless, few studies are performed on the effects of FRP wraps on the slender concrete columns by investigators such as Fitzwilliam et al. (2010), Bisby et al. (2010), Zhong Tao et al. (2004), and Gajdosova et al. (2013).

It can be concluded from these studies that a short concrete column with FRP wraps can be considered as a slender one. This is because the FRP confinement adds additional slenderness to the column. In other word, short columns fail by yielding of the material, while when they are confined by FRP layers, their load bearing capacity increases and they may buckle like slender columns. It should be noticed that addition of FRP layers increases the column flexural stiffness, therefore, it is not appropriate to use slenderness limits proposed by Mari et al. (2005) and Hellesland et al. (2005) which are adopted by concrete structures design codes such as CEN (European Committee for standardization 1992), BSI (British Standards Institution 1997), Code of China 2002 and ACI for FRP wrapped concrete columns. Therefore, this study presents a new relation to compute the critical slenderness ratio for circular FRP confined concrete columns.

2. *Effects of slenderness on column behaviour*

Figure 1 demonstrates the axial load-bending moment diagram for columns with various slenderness ratios and the same eccentricity. These diagrams take account of second-order effects which are functions of slenderness ratio, axial load eccentricity and columns end constraints.

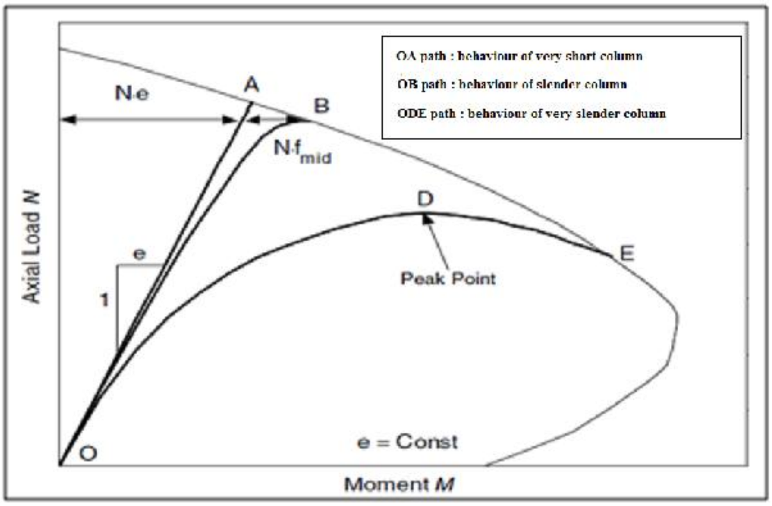

Figure 1. Effects of slenderness on load carrying capacity of columns

In Figure 1, the OA path represents behaviour of very short columns. A very short column fails by yielding of its materials in pressure and only first order moment equal to N×e occurs at failure point. Parameter ‘e’ is load eccentricity in columns. A more slender column possesses a diagram like the OB path. The column is displaced at its middle length and bears an additional second-order moment equal to $N \times f_{mid}$ at its failure point. Parameter f_{mid} is the lateral displacement of the mid height section. However, the column loading path is still ascending and it fails by material fracture. Finally, very slender columns have a descending branch and behave like ODE path. This kind of columns fails by buckling and their axial load capacity reduces considerably due to second-order moment.
It can be concluded that more slender columns sustains lower axial load. Because slenderness is a relative quantity, limit values are necessary for prediction of the columns behaviour.

3. Previous Studies

Many studies are performed to clarify the effects of FRP jackets on circular concrete columns, which in most of them buckling phenomena are neglected. In other word, almost all of the existing design relations are derived for the design of short FRP confined columns. Although there are some studies about the effects of slenderness on the behaviour of confined columns. In this section some of these studies are reviewed.

Ghali et al. (2003) conducted experiments on cylindrical specimens with various heights. Based on their obtained results, they conclude that the specimens strength decrease while slenderness increase and this is true for confined specimens as well as unconfined ones. In another study, Fitzwilliam et al. (2010) examined the behaviour of eighteen sample columns. They determined that increase in slenderness leads to significant decrease in load bearing capacity and ductility of the column, but this decrease is less than when the column is confined using FRP. Another important outcome of their work was that using additional FRP layers around the column does not change its capacity and ductility considerably. Ata Elkarim (2011) studied the effects of slenderness on FRP confined concrete samples and deduced that the efficiency of FRP confinement for very slender columns is not significant. Sadeghian et al. (2008) performed a study on thirty Cylindrical FRP confined concrete samples and reach the same results. Their observations proved that in slender columns addition of FRP layers does not improve strength and ductility substantially. Zhong Tao et al. (2004) studied behaviour of sixteen confined and unconfined long concrete columns with 150 ^{mm} diameter circular cross section. Their obtained results indicated that long confined columns fail in buckling while FRP layers remain intact. Mirmiran (2001) investigated the effects of slenderness and found that addition of FRP layers to long columns is not as efficient as shorter ones. In other words, Addition of FRP layers to a short column increase its axial load bearing capacity more than that of the same but longer column. Belouar et al. (2013) found it through their investigations that first layer of FRP Jacket adds more strength and ductility to the confined column than the next layers. In addition, increase in slenderness of the column leads to decrease in its strength, but ductility grows. Another important outcome of Belouar et al. (2013) study was that there is an inverse relation between concrete strength and the FRP confinement effect on it. It means that the FRP confinement on low-strength concrete specimens produced higher results in terms of strength and strains than for high-strength concrete similar specimens. Therefore, the effect of FRP confinement on the bearing and deformation capacities decreases with increasing concrete strength. Taking the aforementioned studies and their results into account, it is clear that slenderness is a decisive parameter in design of proper FRP confined concrete column. Therefore, an accurate relation to compute the slenderness limit of confined columns is a necessary prerequisite for design practices. In the next section the proposed relation for this purpose will be presented.

4. The proposed relation

Based on Giang et al. (2012) experiment results, the influence of reinforcing rebar in load bearing capacity and slenderness limit of concrete columns is negligible. Consequently, the proposed relation is derived for confined circular concrete column without rebar, but it is also applicable for reinforced concrete columns as well.

The suggested relation is derived based on nonlinear regression of data which are produced by an incremental method. In fact this process can be divided into two steps. At first, for various column dimensions and various concrete strengths and FRP characteristics, the critical length of column at which the Euler buckling load from Engesser’s buckling formula and confined concrete column axial capacity are equal is computed by an incremental method.

At the critical length the following relation between the two mentioned strengths exists:

$$P_M = P_E \tag{1}$$

P_M and P_E are confined concrete column capacity and Euler buckling load, respectively and are derived from the next equations:

$$P_M = f'_{cc}A_c + f_{frp}A_{frp} \tag{2}$$

$$P_E = \frac{\pi^2}{(KL)^2}EI \tag{3}$$

In Eq.2, f'_{cc} and f_{frp} are strength of confined concrete and tensile strength of FRP layers and L is length of column. Also A_c and A_{frp} are areas of the concrete core and FRP jacket, respectively. In Eq.3 factor K is depending on the restraint conditions of the column at both ends. The second term on the right hand side of Eq. 2 can be neglected in comparison to the first one. Therefore, only f'_{cc} is nedded which is computed using the AGT1 relation suggested by Arabshahi (2015):

$$f'_{cc} = f'_{co}\left(1 + 84250.71 \times \left(\frac{f_{frp}^{\ 2.671} \times t^{2.758} \times E_{frp}^{\ 0.108}}{(d \times f'_{co})^{3.206}}\right)\right)^{0.2} \tag{4}$$

In this equation, $f'_{co}$is strength of unconfined concrete. The other parameters are column diameter (d), thickness, tensile strength and modulus of elasticity of the FRP layers (t_{frp}, f_{frp}&E_{frp}). In Eq. 3, EI is the flexural rigidity of the confined column that is calculated using the next equality:

$$EI = E_c I_c + E_f I_f \tag{5}$$

Again, the second term on the right hand side of Eq. 5 is negligible. Therefore, Eq. 1 can be rewritten in the following form:

$$f'_{cc}A_c = \frac{\pi^2}{(KL)^2}E_c I_c \tag{6}$$

In this relation, I_c is moment of inertia of the column cross section. Ec is derived by utilizing bilinear Samaan et al. (1998) equation:

$$E_c = \frac{(E_1 - E_2)}{\left[1 + \left(\frac{(E_1 - E_2)\varepsilon_{cu}}{f_o}\right)^n\right]^{\frac{1}{n}}} + E_2 \tag{7}$$

This relation introduces confined concrete modulus of elasticity as a function of five parameters, namely first and second slopes of the stress-strain curve (E1&E2), ultimate strain (ε_{cu}), reference plastic stress at the intercept to the second slope with the stress axis (f_0) and a factor that control the shape of the stress-strain curve at its transitional range(n). In this study, this factor is selected equal to 1.5 based on Samaan suggestion (Samaan1998).The other four parameters are computed utilizing succeeding equations:

$$E_1 = 3950\sqrt{f'_{co}} \tag{8}$$

$$E_2 = 245.61 f'^{\ 0.2}_{co} + 1.3456\frac{E_f t_f}{d} \tag{9}$$

$$\varepsilon_{cu} = \frac{f'_{cc} - f_o}{E_2} \quad (10)$$

$$f_o = 0.872 f'_{co} + 0.371 \frac{2 f_f t_f}{d} + 6.258 \quad (11)$$

With required relations, the first step will be presented. At this step, many data samples are produced. For this purpose, all the column and FRP layers variables except the column length are selected and the critical length is computed for this set of variables using Eq. 6. Then, the other variables are changed incrementally and for each set, the critical load is calculated. Using this method, the required data samples for the second step which is nonlinear regression are obtained. In this work, more than 10000 sample data produced at the first step. Finally in the second step, using numerical methods for nonlinear regression of data, the following relation for slenderness limit is derived:

$$\lambda = \frac{11.58}{\left(1+84250.71\times \frac{f_{frp}^{2.671}\times t^{2.758}\times E_{frp}^{0.108}}{d\times f'_{co}{}^{3.206}}\right)^{0.2}}^{-0.391} = \frac{11.58}{\left(\frac{f'_{cc}}{f'_{co}}\right) AGT1}^{-0.391} \quad (12)$$

5. Performance of the proposed relation

Thus the intention of this study is to present a relation for calculation of slenderness limit, it seems necessary to describe the critical slenderness clearly. For a FRP confined concrete column, the critical length is the length at which the column never buckles at any stress level.

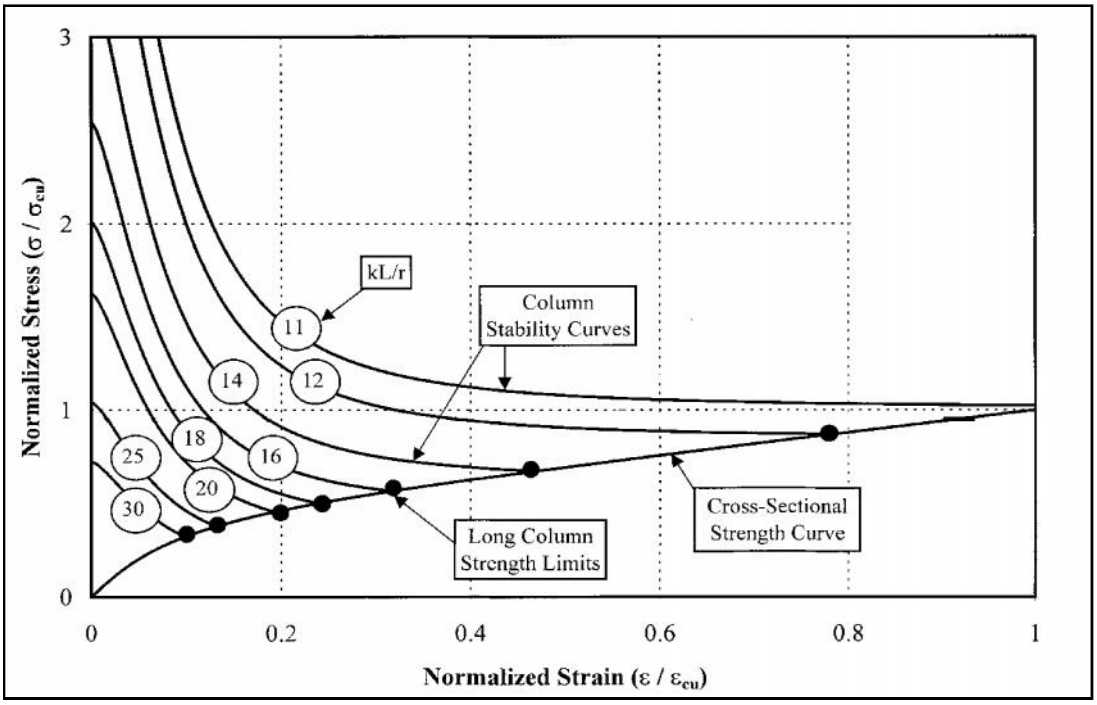

Figure2. TheEulerbucklingloadsandaxialcapacityofa FRP wrappedsamplecolumn with various slenderness

In other words, for a confined column with its critical length, the Euler buckling load becomes equal to the confined column strength at its ultimate strain. Therefore, a shorter confined concrete column never experience buckling. Figure 2 depicts what was described before for a sample confined column. It is evident that for this column, the critical slenderness is equal to 11.

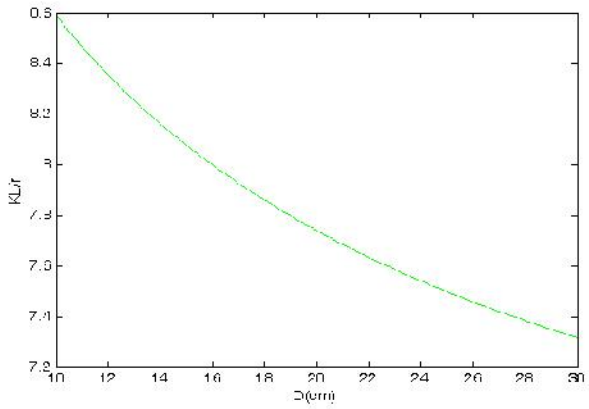

Figure 3. Variation of slenderness limit with column diameter

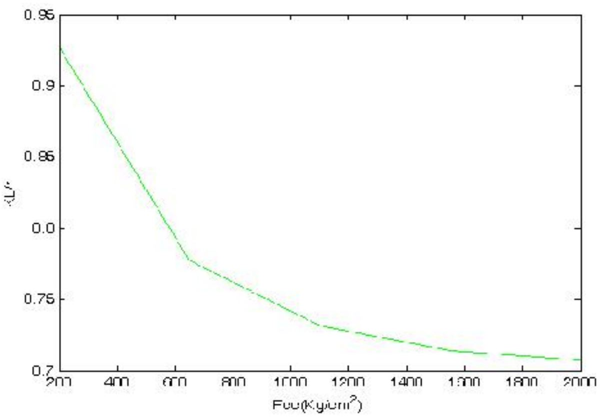

Figure 4. Variation of slenderness limit with concrete strength

Figures3 to5 demonstrates variation of the slenderness limit with different parameters for a circular column with the following characteristics:

$$f'_{co} = 380\frac{kg}{cm^2}, E_{frp} = 1510000\frac{kg}{cm^2}, f_{frp} = 21000\frac{kg}{cm^2}, t = 0.081cm, d = 15\ cm$$

It is observed that increase in the diameter of the columns leads to decrease in the slenderness limit, surprisingly.This can be defined easily using figure2. Increase in the column diameter will decrease the confined concrete strength, but it increases the column cross section such that the axial load bearing capacity of the column rises. It means to shift up the cross sectional strength in Figure2. Therefore,a less slenderness limit is possible.There is an inverse relation between the concrete strength and slenderness limit which isillustrated in Figure4 and can be justified in the same manner.

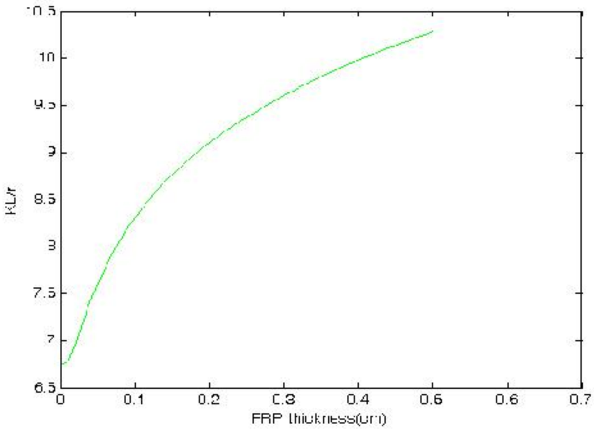

Figure 5. Variation of slenderness limit with FRP thickness

On the other hand, increase in FRP characteristics such as thickness, strength and modulus of elasticity, increases the confined concrete strength and makes it possible to rise the slenderness limit for the column.

6.*Conclusion*

FRP confinement improves ductility and strength of concrete structural members. But this method in slender columns is not as efficient as in the short members. In addition, a concrete column which is counted to be short can be considered slender after addition of FRP jacket because confinement supplements an additional slenderness effect to the column. Because of the mentioned reasons, a slenderness limit is necessary to judge whether FRP confinement develops the concrete structure strength and ductility or not. Hence, an equation to compute slenderness limit for FRP confined concrete columns is proposed in this paper using numerical sampling and nonlinear regression. The suggested relation take account of different parameters such as column dimensions, concrete strength and FRP characteristics.

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