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Numerical estimation for strengthening length of circular RC columns using outer steel tube

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ABSTRACT

This paper introduces an improved design equation to evaluate the resisting capacity of circular reinforced concrete (RC) columns partially strengthened with outer steel tube. To evaluate the resisting capacity of a partial CFST column, a numerical model proposed to consider the bond-slip effect at the interface of steel tube and in-filled concrete is used to conduct parametric studies for the introduction of a design equation. Moreover, parametric studies make it possible to introduce a design equation for determining the optimum length of outer steel tube which produces partial CFST circular columns.

1. INTRODUCTION

Recent increasing requirements for enhancing seismic performance in RC structures has led to the introduction of various strengthening methods to RC columns in particular. Since the seismic load causes lateral drift, which introduces additional moments to columns in a structure, the strengthening of RC columns has been focused on increasing the moment resisting capacity, and steel plate are usually adopted. Many experimental and numerical studies have also been performed for concrete filled steel tube (CFST) columns, which are equivalent to the strengthening of RC columns with outer steel tube (Ren et al., 2017; Ma et al., 2018). Many numerical models have also been introduced in parallel with the experimental studies to more precisely simulate the composite behavior of the structure (Hwang & Kwak, 2018; Hua et al., 2019).

Despite the structural advantages, however, the high construction cost of a full CFST has limited its popular use as an alternative structure. To minimize the construction cost while maintaining the structural efficiency, accordingly, a partial CFST has been considered (Lee et al., 2018; Tian et al., 2018).

This paper suggests a design guideline for partial CFST columns that can improve the required structural strength of RC columns while minimizing an increase in the strengthening cost. Since a larger bending moment is developed at the end of the column,

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partial strengthening will be realized at the end region of the RC column. The design suggestion for strengthening the RC column is focused on how to increase the moment resisting capacity of the column by partial CFST. Parametric studies based on numerical approach are performed to determine the effective cover length for the design of a partial CFST column. Finally, a design equation that can be used to simply estimate the effective cover length in a partial CFST column is suggested on the basis of a linear regression of the numerical results obtained from parametric studies.

2. System suggestion: Partial CFST column

Basically, when a typical section of RC column is designed, the resisting capacity for the axial force and bending moment will be evaluated. As shown in Fig. 1, a RC column subjected to lateral force (P_H) at the top face will collapse when the bending moment at the bottom ($M = P_H \times L$) reaches the resisting capacity of the RC section (M_{RC}). However, a partial CFST column strengthened within the length of *H* can resist larger lateral force than the original RC column, and three failure scenarios of ① failure in CFST, ② balanced failure, and ③ failure in the RC column can be examined. The red line in Fig. 1 describes the moment distribution at the balance failure (②) of a partial CFST column determined by applying the lateral load $P_{H,bal}$, in which case the original RC and CFST parts fail at the same time at section A-A and the end face, respectively. This means that the bending moment at the fixed end ($P_{H,bal} \times L$) will exactly correspond with the resisting capacity of the CFST section (M_{CFST}) when the bending moment at section A-A ($P_{H,bal} \times (L - H)$) reaches the resisting capacity of the original RC section (M_{RC}). When the maximum resisting capacity of the CFST section is less than point ②, the CFST part fails first before the original RC part reaches failure, and this situation will occur in the case of using a relatively thinner steel tube than necessary (see point ① in Fig. 1). On the other hand, even though the resisting capacity of the CFST section is increased and becomes larger than point ② with an increase in the thickness of the steel tube, the resisting capacity of the partial CFST column does not increase in proportion to an increase in the thickness of the steel tube because the RC part at section A-A will reach failure first (see point ③ in Fig. 1). Accordingly, the effective design of a partial CFST column will be derived from the balanced failure, and the corresponding length of exterior steel tube that leads to the optimum design in a partial CFST column is defined as the effective cover length H_{eff} in this paper.

To simulate the composite behavior of concrete and steel tubes at the CFST part, a proper assumption at the interface between the in-filled concrete and the steel tube should be considered. In this paper, it is assumed that sufficient bond stress occurs at the interface of the composite structure. However, differently from the perfect bond assumption in which the complete compatibility of strains between the in-filled concrete and the steel tube is based, the CFST part accompanies the bond-slip along the interface of both structural components with an increase of the deformations and internal forces delivered through the interaction between the in-filled concrete and the steel tube. To address the composite behavior at the interface, an improved numerical model, which was proposed by the authors in a previous paper (Hwang & Kwak., 2018), is used in this paper.

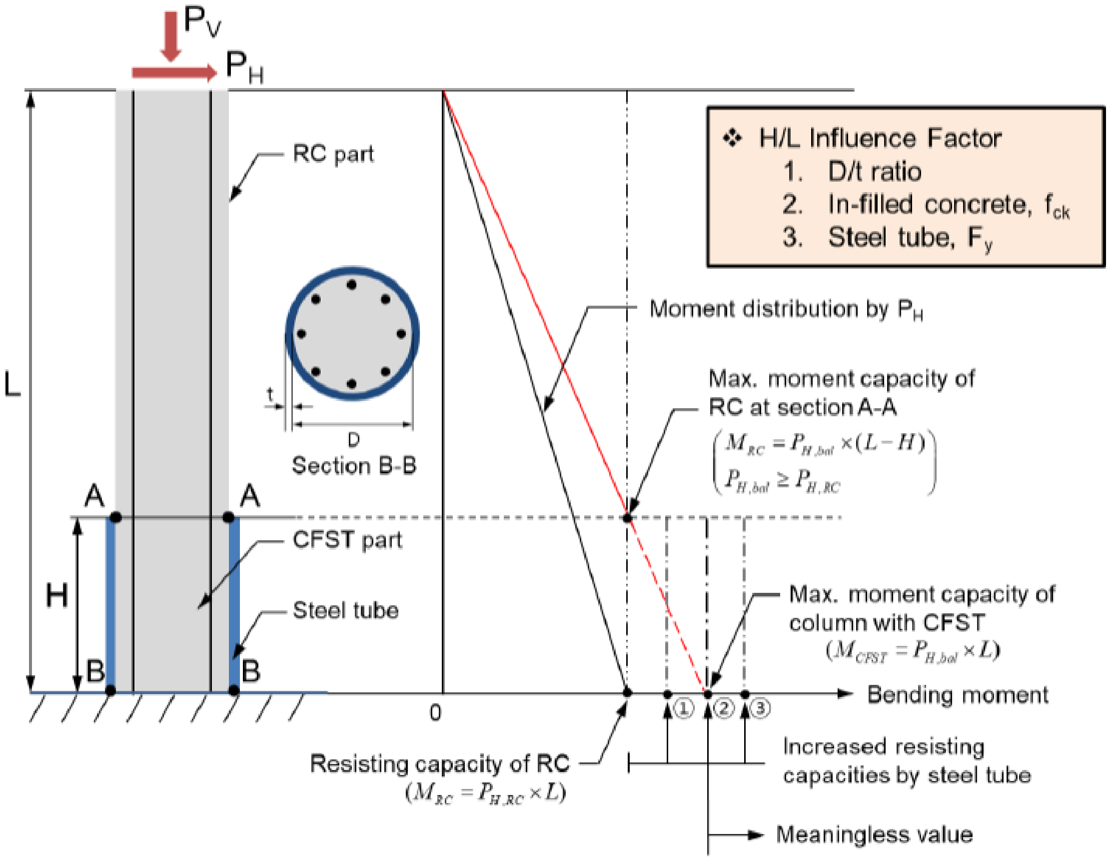


Fig. 1 Moment state of the partial CFST subjected to lateral load

3. Effective cover length in partial CFST column

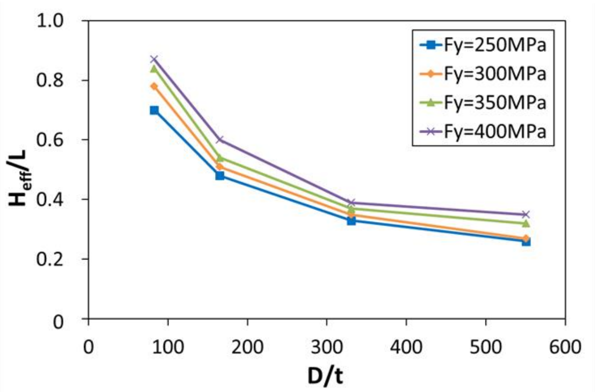
As mentioned before, an increase of resistant capacity in a partial CFST column according to the change in the thickness of the exterior steel tube is very limited because the failure usually starts at the border between the original RC column and the steel tube. In addition, the resisting capacity of the CFST column increases in proportion to an increase in the thickness of the steel tube, whereas the original RC column keeps its resisting capacity without any change. This means that the effective cover length (H_{eff}) in the steel tube (see Fig. 1) should be determined to derive the balance failure, which means that both Section A-A and Section B-B in Fig. 1 reach their ultimate moment resisting capacities at the same time, because this condition will produce the most effective design of the partial CFST column.

To directly evaluate the effective cover length H_{eff} on the basis of the section properties (the diameter D of in-filled concrete and the thickness t of steel tube) and the material properties of concrete and steel (the compressive strength of concrete f_{ck} and the yield strength of steel F_y), a simple equation is introduced in this paper through parametric studies considering the change in the design variables. Since the ultimate resisting capacity of partial CFST columns depends on the confinement effect, which cannot be quantified through the simple equilibrium equation and compatibility condition in a section, and the bond-slip effect, which has not been restricted in a section but has been varied along the span length, the derivation of an analytical simple design equation that can effectively consider the change in design variables was almost impossible, and that is why a simple regression equation is introduced in this paper. A cantilevered partial CFST column, as shown in Fig. 1, is considered for parametric studies and its corresponding basic section properties are as follows: total length of L = 660.8 *mm,* section diameter of core concrete D = 165.2 *mm*, and steel ratio of reinforcement embedded in core concrete ρ = 2%. The vertical and lateral forces are applied at the top face of the column. Moreover, four different thicknesses of steel tube (t = 0.3, 0.5, 1, and 2 *mm)*, five different compressive strengths of in-filled concrete (f_{ck} = 25, 30, 35, 40, and 45 *MPa*), and, in advance, four different yield strengths of steel tube (F_y = 250, 300, 350, and 400 *MPa*), whose combination produces 80 different cases, are considered in the parametric studies. Even though a maximum D/t ratio of about 370 is being considered as the upper limit value in current design codes (AISC, 2010; AASHTO, 2011) to prevent the occurrence of local buckling, this paper considers D/t ratio up to 550.7 in the parametric study to trace the variation of the ultimate strength of partial CFST column with D/t ratio.

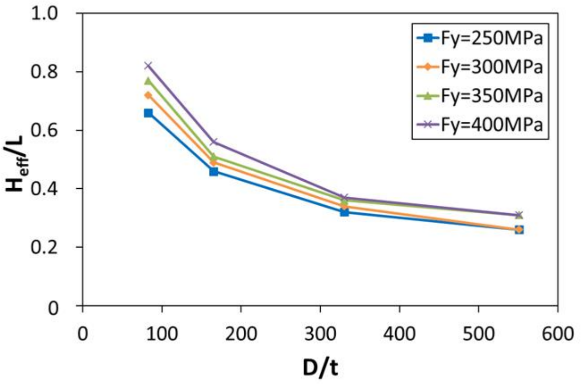
Upon the basis of the FE idealization adopted in a previous paper by the authors (Hwang & Kwak, 2018), ABAQUS (2017) is used in the numerical analyses, and 8-node 3-D solid elements (named C3D8R element in ABAQUS) are applied in the numerical modeling of both the in-filled concrete and the outer steel tube, respectively. (see Fig. 2) A convergence test of the partial CFST column is performed to determine the appropriate mesh size. To the numerical model, only the lateral force P_H was applied to evaluate the bending moment capacity of specimens. The obtained results can be found in Fig. 3. In order to normalize the geometrical dimensions, the thickness of the steel tube is expressed by the D/t ratio and the obtained effective cover length by H_{eff}/L.

As shown in Fig. 3, even though the decreasing rate of H/L according to an increase of D/t is affected by the compressive strength of in-filled concrete, the overall tendency of the effective cover length of steel tube, which shows an increase with a decrease of the D/t ratio and an increase of F_y, is maintained. This means that a partial CFST column wrapped with a thicker steel tube should be strengthened with a longer steel tube to exhibit the maximum moment resisting capacity increased by the addition of steel tube. Conversely, the use of a thinner steel tube gives converged results in short effective cover length of steel tube because the contribution of steel tube to the moment resisting capacity is very limited. Furthermore, the influence of the yield strength of the steel tube on the effective cover length of the steel tube has been enlarged with a decrease of the D/t ratio.

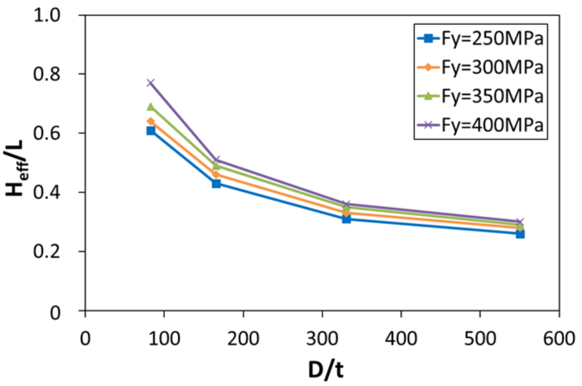
From the obtained results, an equation to estimate the effective cover length of steel tube in a partial CFST column is designed. In order to analyze the variation in the slope of curves in Fig. 3 according to the material properties, first the obtained results are normalized again by F_y/f_{ck}. The results for the case of F_y/f_{ck}=10 are shown in Fig. 4 as an illustration. As shown in this figure, the values of H_{eff}/L present consistent variation with respect to the ratio of D/t, regardless of the different combination of F_y and f_{ck}, and this means that Eq. (1) below can be considered to describe the relation between H_{eff}/L and D/t.



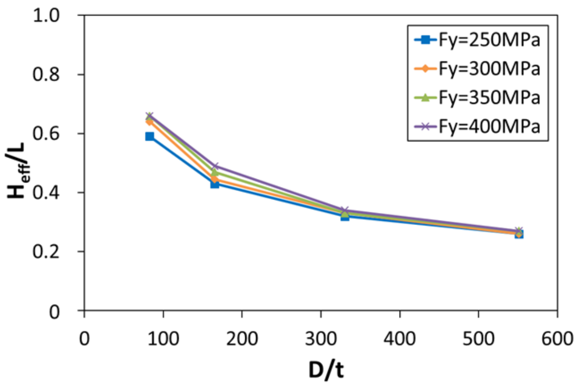
(a) fck = 25 MPa



(b) fck = 30 MPa



(c) fck = 35 MPa



(d) fck = 45 MPa

Fig. 3 Effective cover length according to the thickness of steel tube

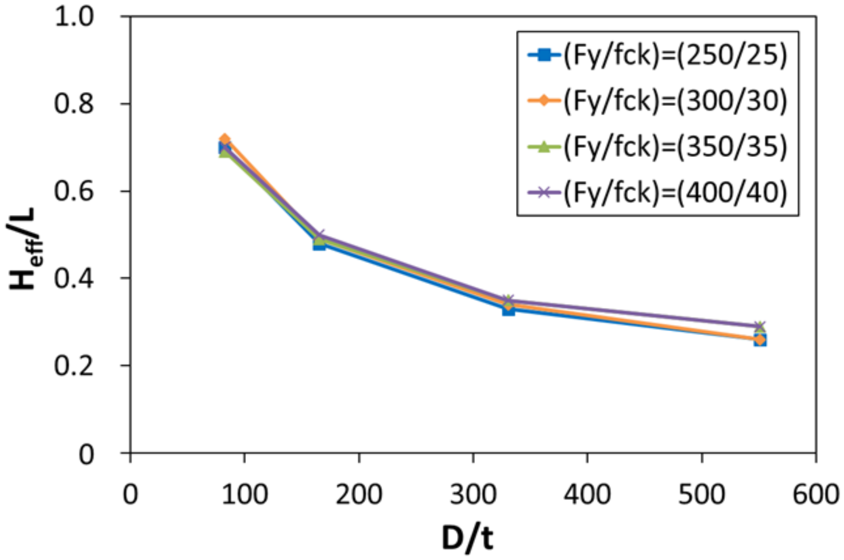


Fig. 4 Effective cover length according to the thickness of steel tube at Fy/fck=10

$$H_{eff}/L = \frac{\alpha}{\sqrt{D/t}} \quad (1)$$

where α represents a constant reflecting the variation in the material properties. From all the curves normalized again by F_y/ f_{ck}, the corresponding values of α can be calculated and then plotted with respect to the ratio of F_y/ f_{ck}, as shown in Fig. 5. Moreover, the linear regression is used to obtain the expression for α. The exactness of the introduced equation has been verified through comparison with the numerical results obtained, and the results can be found in Fig. 6.

$$\alpha = 0.18 \cdot \left(\frac{F_y}{f_{ck}}\right) + 4.5 \quad (2)$$

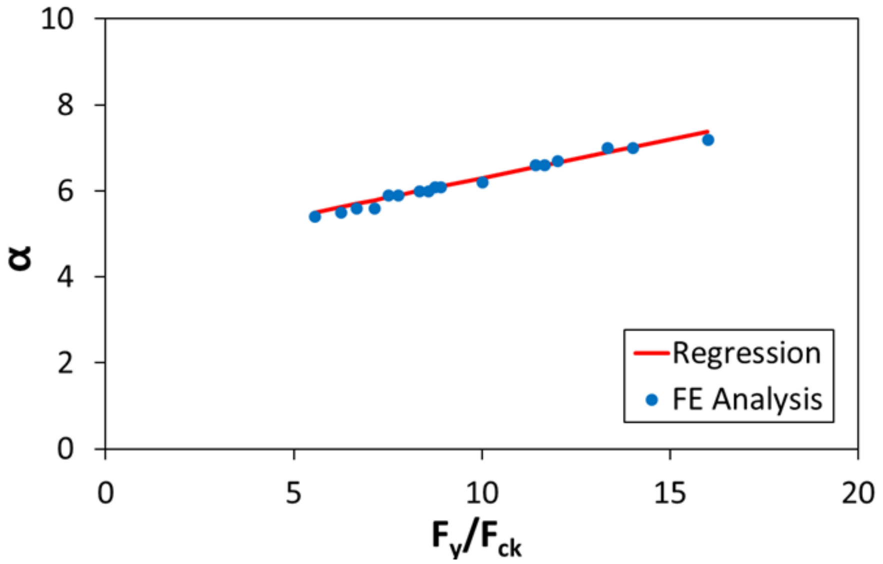
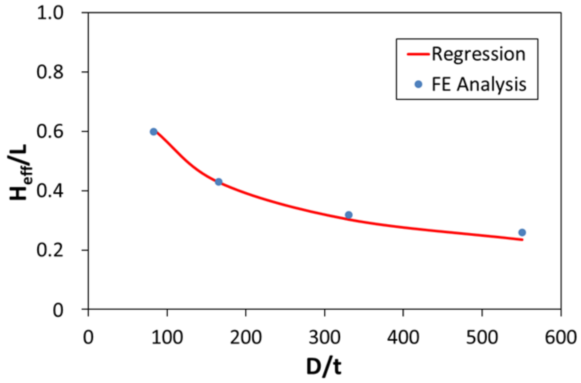
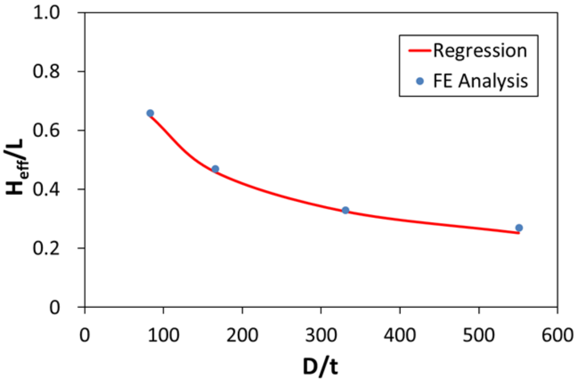


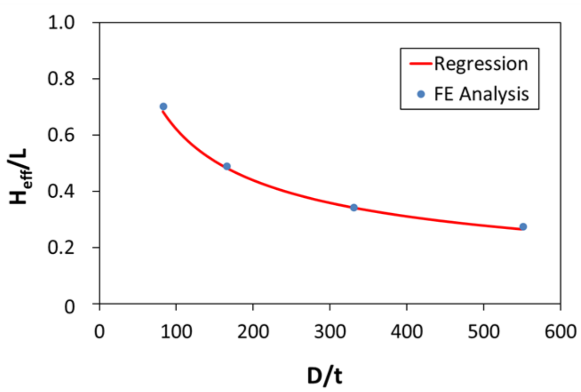
Fig. 5 Constant alpha with various Fy/fck



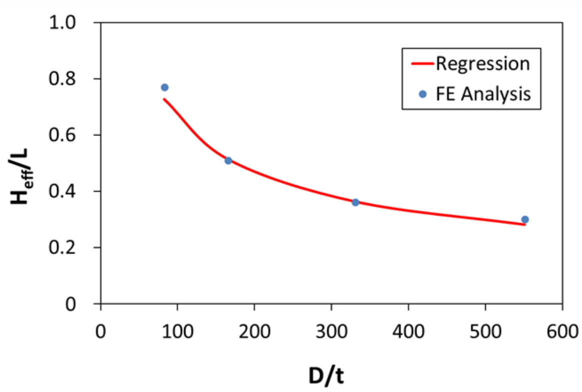
(a) Fy/fck = 6.25



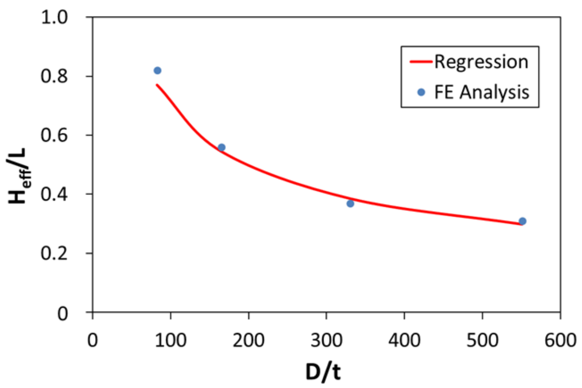
(b) Fy/fck = 7.78



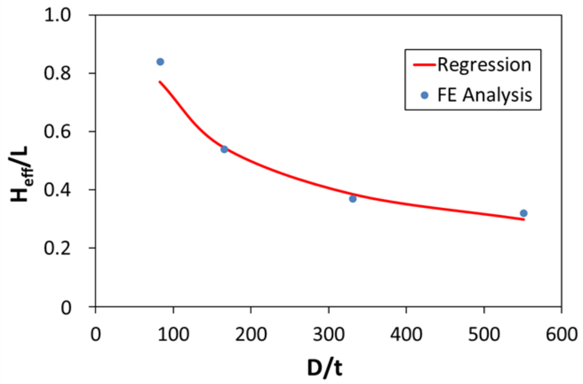
(c) Fy/fck = 10.00



(d) Fy/fck = 11.43



(e) Fy/fck = 13.33



(f) Fy/fck = 14.00

Fig. 6 Estimation of the effective cover length by suggested design equations

4. CONCLUSIONS

This paper introduces a design equation to determine the effective cover length of a partial CFST column through parametric studies on the basis of a numerical model considering the bond-slip behavior along the interface between in-filled concrete and exterior steel tube. Since the partial CFST column makes it possible to maximize the strengthening effect in a RC column without sacrificing the bending moment capacity comparing to the full CFST column, it can be considered one of the representative strengthening methods in RC columns.

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