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# FE analysis of circular CFT columns considering bond-slip effect: Evaluation of ultimate strength

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ABSTRACT

In this paper, a simple design equation to predict the resisting capacity of circular CFT columns is introduced, and the accompanying design procedure entails two phases: construction of the linearized P-M interaction diagram for a circular CFT column section and its adjustment according to the slenderness ratio. To construct the linearized P-M interaction diagram of circular CFT columns without a rigorous nonlinear analysis, simple equations are proposed in this paper. In advance, on the basis of the numerical results obtained by the use of the analytical model introduced in the previous paper, the ultimate resisting capacity reduction factors are designed through a curvilinear regression, and the use of these reduction factors makes it possible to determine the ultimate resisting capacity of slender CFT columns without any rigorous nonlinear analysis. Finally, the efficiency of the introduced design equation is verified on the basis of the comparison of the ultimate resisting capacities calculated in this paper with those determined by rigorous nonlinear analyses and by the AISC design guideline and the Eurocode.


## 1. Introduction

Concrete filled steel tube (CFT) columns have been increasingly used in buildings and bridges, owing to their excellent structural behavior and the numerous benefits induced from the use of steel tube on the exterior surface of concrete column. Various experimental and numerical studies have been continuously performed to examine the overall performance of CFT columns [1–6], and the development and improvement of design codes such as the AISC design guideline [7] and the Eurocode [8] have contributed to the outcomes of these studies.

Currently, many design codes provide design provisions for CFT columns [9–11], and the AISC design guideline and the Eurocode may be considered as two representatives among these design codes. Since the design of CFT columns begins from an exact evaluation of the ultimate resisting capacity represented by the P-M interaction diagram, all the design codes including the AISC design guideline and the Eurocode provide their own evaluation procedures to construct the P-M interaction diagram. However, the evaluation procedures described in design codes may underestimate or overestimate the ultimate resisting capacity and finally lead to inaccurate design of CFT columns.

To improve the evaluation procedures, accordingly, many experimental and numerical studies have been performed [12–14]. Choi et al. [12] suggested equations to determine the P-M interaction diagrams of square CFT columns by using the experimental results of other researchers. Since the P-M interaction diagram constructed by the AISC design guideline [7] produces a rather conservative maximum moment under a lower level of axial load, the suggested equations can effectively be used to obtain improved results. However, since the method was developed on the basis of a limited amount of experimental data obtained from different experiments and the applicability of the method was tested only for compact sections, it would not be appropriate to directly apply the method to relatively slender CFT columns without additional verification of its reliability.

Recently, Moon et al. [13] suggested a new drawing method to construct the P-M interaction diagram on the basis of the results obtained by numerical analyses. In particular, to precisely evaluate the resisting capacity of a CFT column, the interface behavior between the in-filled concrete and the steel tube was taken into account through the use of gap elements. While this approach gives a relatively accurate prediction for the resisting capacity of CFT columns, its use in design practice will be very limited because of the difficulty in constructing the P-M interaction diagram by the plastic stress distribution method (PSDM), instead of using simple equations.

Furthermore, Dai et al. [14] performed numerical analyses for elliptical sectional CFT columns subjected to axial force with a hard-contact assumption between in-filled concrete and steel tube. They also suggested a modification of design equations in the Eurocode to evaluate the resisting capacity of and elliptical sectional CFT column through the use of the same evaluation procedures as employed for a circular CFT column, but additional consideration or modification of design equations in the Eurocode was not included.

In spite of many related studies, additional improvement of design equations for an exact evaluation of the ultimate resisting capacity

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of CFT columns is still required, as mentioned by many researchers [12–14], because the problem of conservativeness in the construction of the P-M interaction diagram has not been mitigated. Since the design of a CFT column is performed by the use of design equations rather than by conducting a rigorous numerical analysis for CFT columns, conservative evaluation of the P-M interaction diagram by design equations directly leads to underestimation of the resisting capacity in practice.

To address this problem in field applications and to consider all the nonlinear factors in design effectively, an improved design equation to determine the P-M interaction diagram of slender CFT columns is introduced in this paper. On the basis of the numerical results obtained by the use of the analytical model introduced in the previous paper, parameter studies are performed on CFT columns with various structural dimensions, and more delicate comparisons of numerical results follow. From a curvilinear regression of parameter studies, the reduction factors to adjust P-M interaction diagram by length of CFT columns are proposed. With applying proposed reduction factors in preliminary design stage, the P-M interaction diagram for slender circular CFT columns is easy to construct without conducting additional elaborate nonlinear analyses. Moreover, the ultimate resisting capacities of slender circular CFT columns estimated by the proposed design equation are compared with those calculated by a rigorous nonlinear analysis and determined by the design equations in the AISC design guideline and the Eurocode with the objective of establishing the accuracy of the proposed design equation.

## 2. P-M interaction diagram by design codes

Evaluation of the ultimate resisting capacity and design of CFT columns have been conducted according to the evaluation procedure specified in most design codes, and the AISC design guideline [7] and the Eurocode [8] are the most popularly adopted in design practice because of their simple design procedure. Since the design procedure for a CFT column begins from the construction of the P-M interaction diagram for a CFT column section, the accuracy of the design will depend on the accuracy of the constructed P-M interaction diagram.

To construct the P-M interaction diagram, the AISC design guideline proposes basically two different approaches, which are based on variations of the plastic stress distribution method [15]: a simplified plastic stress distribution method and a more complex strain compatibility method [16]. In both approaches, construction of the P-M interaction diagram starts from the evaluation of two anchor points corresponding to pure axial load (point A in Fig. 1) and pure bending moment (point B in Fig. 1), and more details of the related equations can be found elsewhere [7].

Upon determining both anchor points, a simplified plastic stress distribution method determines the third point corresponding to a member force combination of 20% of pure axial load and 90% of pure bending moment (point C in Fig. 1(a)), and then these three boundary points are linearly connected to construct the P-M interaction diagram. As shown in Fig. 1(a), this method introduces a very simple construction procedure but provides a conservative assessment of the resisting capacity of CFT columns, and its conservativeness is usually enlarged with an increase of the compressive strength of concrete [13]. In particular, point C shows a large difference from the balanced strain condition of CFT columns with a relatively small slenderness ratio.

On the other hand, the strain compatibility method constructs the P-M interaction diagram by connecting four boundary points, as shown in Fig. 1(b). This means that two more boundary points, point C and point D, need to be determined in addition to the two anchor points, point A and point B. First, point C corresponds to a plastic neutral axis location that results in the same flexural strength as point B, but including axial compression. Next, point D corresponds to an axial compression of one half of that determined for point C.

Once the nominal strength envelope is determined, length effects according to the slenderness ratio are included by reducing the three boundary points A, C, and D to points A', C′, and D', respectively (see Fig. 1(b)). The slenderness reduction factor λ applied to each point is the same and has a value of $\lambda = P_n/P_{no}$, where $P_n$ and $P_{no}$ are the critical load (corresponding to point A' in Fig. 1(b)) and the pure axial load (corresponding to point A in Fig. 1(b)), respectively, and can be determined as follows:

$$P_{no} = 0.95 f_{ck} A_c + F_y A_s + F_{sr} A_{sr} \tag{1}$$

$$\begin{aligned} P_n &= P_{no}\left(0.658^{\frac{P_{no}}{P_e}}\right), \frac{P_{no}}{P_e} \le 2.25 \\ P_n &= 0.877 \cdot P_e, \frac{P_{no}}{P_e} > 2.25 \end{aligned} \tag{2}$$

where $P_e = \pi^2 EI_{eff}/(KL)^2$, $f_{ck}$ is the compressive strength of concrete, $F_y$ and $F_{sr}$ are the yield strength of steel tube and reinforcement, and $A_c$, $A_s$, and $A_{sr}$ are the area of the in-filled concrete, steel tube, and reinforcement, respectively. In advance, the effective stiffness $EI_{eff}$ shall be $EI_{eff} = C_3 E_c I_c + E_s I_s + E_{sr} I_{sr}$, where $E_c I_c$, $E_s I_s$, and $E_{sr} I_{sr}$ represent the bending stiffness of the in-filled concrete, steel tube, and internal reinforcement, respectively, $C_3 = 0.6 + 2\left[\frac{A_s}{A_c + A_s}\right] \le 0.9$ is a coefficient for calculating the effective rigidity in a CFT section, and K is the effective buckling length factor.

Eurocode [8] also suggests two different approaches, a general approach and a simplified approach, to determine the ultimate resisting capacity of CFT columns. Since the general approach is based on the nonlinear analysis of a CFT section considering the material nonlinearity of constituent materials, its use in design practice is very limited even

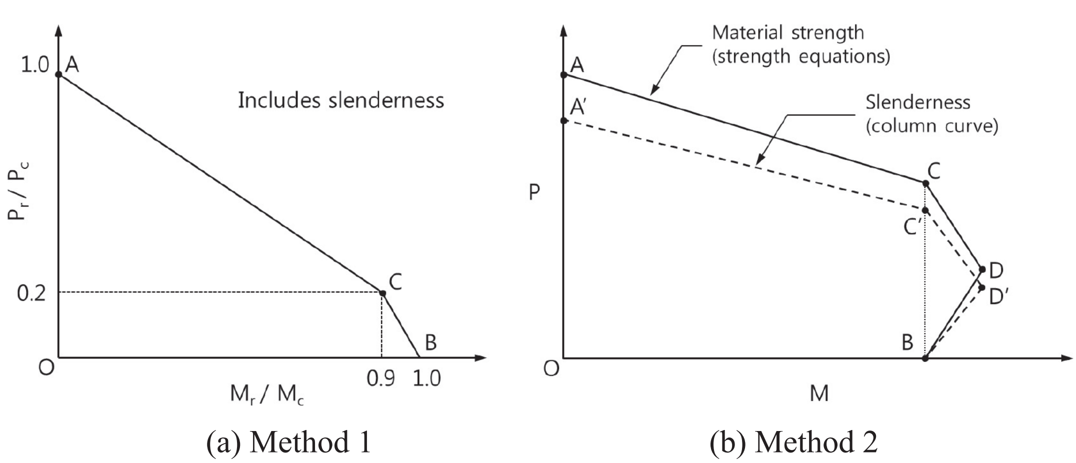


**Fig. 1.** Construction of the P-M interaction diagram for a CFT column by the AISC design guideline [7].