Resilient Structures and Sustainable Construction
Edited by Pellicer, E., Adam, J. M., Yepes, V., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-4-8

ULTIMATE STRENGTH OF CONCRETE FILLED SQUARE STEEL TUBULAR BEAM-COLUMNS

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The objective of this study is to examine the ultimate strength of CFT columns. The range of the axial load ratio and the slenderness ratio in which CFT beam-columns reach the full plastic moment are examined on the basis of the strength formulas specified by *AIJ Recommendation for Limit State Design of Steel Structures*. The CFT columns are subjected to the constant axial compressive force and the monotonic moment at the one end, as the analytical parameters the axial load ratio and slenderness ratio are selected. The analysis is carried out by the shooting method. Bending moment-rotational angle relationships are calculated by the shooting method and the maximum strengths of CFT columns are obtained. When the value obtained by multiplying the axial load ratio and the second power of the slenderness ratio is 0.05, the maximum strength reach 95% of the full plastic moment under the condition that the axial load ratio value is less than or equal to 0.75. When the value obtained by multiplying the axial load ratio and the second power of the slenderness ratio is 0.1, the maximum strength reach 95% of the full plastic moment under the condition that the axial load ratio value is less than or equal to 0.5.

Keywords: Full plastic moment, Axial load ratio, Slenderness ratio, Effective length to section depth ratio, Maximum bending strength, Moment gradient ratio.

1 INTRODUCTION

Design formulas for concrete filled steel tubular (CFT) beam-columns are shown in *Architectural Institute of Japan Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures* (afterwards, referred to as CFT Recommendations) (AIJ 2008). Regarding CFT beam-columns subjected to constant axial compressive force and bending moment in CFT Recommendations, CFT beam-columns whose effective length to section depth ratio (l_k/D) is less than or equal to 4 are called short columns, CFT beam-columns whose l_k/D is more than 4 and less than or equal to 12 are called intermediate columns and CFT beam-columns whose l_k/D is more than 12 are called slender columns. Design formulas for short columns, intermediate columns and slender columns are different. The ultimate strength of the short columns is calculated by general superposed strength formulas and the ultimate strength of the slender columns is calculated by superposed strength formulas considering buckling.

Properties of CFT structures are close to those of steel structures. Design formulas for steel beam-columns are shown in *Recommendation for Limit State Design of Steel Structures (*afterwards, referred to as LSD Recommendation) (AIJ 2010). As conditions for beam-columns to reach the full plastic strength and has enough deformation capacity in LSD Recommendation, the axial load ratio, the slenderness ratio and the moment gradient ratio are given. It is considered that the axial load ratio, the slenderness ratio and the moment gradient ratio greatly influence the strength of CFT beam-columns, however the above factors are not used in the present CFT Recommendations as the explicit strength evaluation index.

The objective of this study is to examine the ultimate strength of CFT columns. The range of the axial load ratio and the slenderness ratio in which CFT beam-columns reach the full plastic moment are examined on the basis of the strength formulas specified by LSD Recommendation.

2 ANALYSIS

2.1 Limitation of Axial Load Ratio and Slenderness Ratio in LSD Recommendation

In LSD Recommendation, as shown in Table 1, beam-columns are categorized from C-I to C-III. Categorized regions are expressed by the axial load ratio, n_y, the flexural buckling slenderness ratio, λ_c, the slenderness ratio of beam-columns subjected to in-plane bending in a frame, ${}_f\lambda_c$, and the flexural buckling limit strength, ${}_fN_c$. The axial load ratio, n_y, flexural buckling slenderness ratio, λ_c, and moment gradient ratio, κ, are defined by Eqs. (1), (2), and (3), respectively.

$$n_y = N / {}_sN_y \tag{1}$$

$$\lambda_c = \sqrt{{}_sN_y / N_e} \qquad (N_e = \pi^2 {}_sE_sI / l_c^2) \tag{2}$$

$$\kappa = M_2 / M_1 \qquad (|\kappa| \le 1.0) \tag{3}$$

In Eq. (1), N is axial compressive force and ${}_sN_y$ is axial yield load of steel. In Eq. (2), ${}_sE$ is the Young's modulus of steel tube, ${}_sI$ is the moment of inertia of the steel tube and l_c is the unbraced length. The end moment, M_1, is numerically larger than M_2. The value of M_2/M_1 is positive when the member is bent in reverse curvature. In addition, LSD Recommendation has the provision of $\lambda_c \le 2$. Beam-columns in which a plastic hinge is formed have to satisfy Eqs. (4) and (5).

$$For \quad -0.5 < M_2 / M_1 \le 1.0, \quad n_y \cdot \lambda_c^2 \le 0.10(1 + M_2 / M_1) \tag{4}$$

$$For \quad -1 < M_2 / M_1 \le -0.5, \quad n_y \cdot \lambda_c^2 \le 0.05 \tag{5}$$

Table 1. Category and limitation of axial load ratio and slenderness ratio in LSD Recommendation.

Category of beam-columns	**Axial load ratio**	**Axial load ratio and slenderness ratio**
C-I	$n_y \le 0.75$	$n_y \cdot {}_f\lambda_c^2 \le 0.25$
C-I a plastic hinge is formed		$For \quad -0.5 < M_2 / M_1 \le 1.0, \quad n_y \cdot \lambda_c^2 \le 0.10(1 + M_2 / M_1)$ $For \quad -1 < M_2 / M_1 \le -0.5, \quad n_y \cdot \lambda_c^2 \le 0.05$
C-II, C-III	$N / {}_fN_c \le 1.0$	-

2.2 Analytical Model

The analytical model is shown in Figure 1. CFT columns with a length l_c are subjected to the constant axial compressive force, N, and the bending moment at the one end M_1. The member is simply supported at both ends.

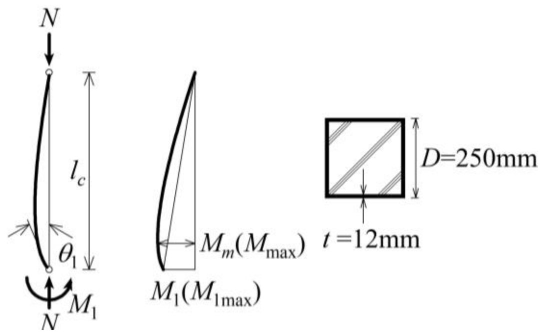


Figure 1. Analytical model.

2.3 Stress-Strain Relationship

The stress-strain relationship of steel tube is assumed to be elastic-perfectly plastic and the stress-strain relationship of concrete is calculated by Eqs. (6) and (7) (AIJ 1991). Figure 2 shows the stress-strain curves of steel tube and concrete.

$$\sigma = \left\{1 - \left(1 - \frac{\varepsilon}{\varepsilon_m}\right)^a\right\} {}_c\sigma_B \qquad (\varepsilon < \varepsilon_m) \tag{6}$$

$$\sigma = {}_c\sigma_B \qquad (\varepsilon_m \le \varepsilon) \tag{7}$$

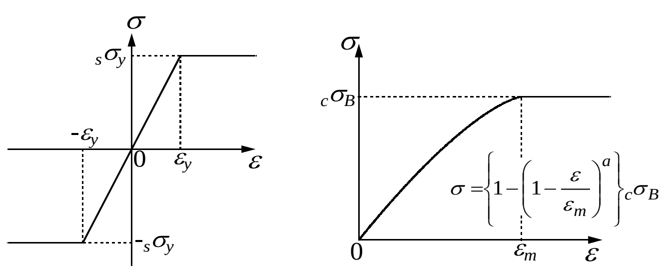
In Eqs. (6) and (7), ${}_c\sigma_B$ is the compressive strength of concrete. In Eq. (6), the index, a, and the strain at the compressive strength, ε_m, are calculated by Eqs. (8) and (9), respectively.

$$a = \frac{{}_cE' \times \varepsilon_m}{{}_c\sigma_B} \tag{8}$$

$$\varepsilon_m = 0.93 \times {}_c\sigma_B^{\frac{1}{4}} \times 10^{-3} \tag{9}$$

In Eq. (8), ${}_cE'$ is calculated by Eq. (10).

$${}_cE' = (3.32 \times \sqrt{{}_c\sigma_B} + 6.9) \times 10^3 \tag{10}$$



(a) steel. (b) concrete.

Figure 2. Stress-Strain curves.

2.4 Analysis Assumptions and Analysis Method

As analytical assumptions, 1) Bernoulli-Navier's assumption, 2) infinitesimal deformation theory and 3) nonlinear elastic material with the stress-strain relationship shown in Section 2.3 (not considering strain reversal) are used. The relationship between the bending moments and rotational angles is calculated by the column deflection method (CDC method). In this method, the bending moment-curvature relationship is calculated by using the above assumptions and converting the boundary value problem to the initial value problem carries out the analysis.

2.5 Analytical Parameter

As the analytical parameter, the value of α in Eq. (11) is selected on the basis of Eq. (4), that is, the axial load ratio, n_y, and the slenderness ratio, λ_c, are selected. Since the loading condition is the constant axial compressive force, N, and the bending moment at the one end, M_1, the value of κ is equal to 0.

$$n_y \cdot \lambda_c{}^2 \leq \alpha(1+\kappa) = \alpha \tag{11}$$

In this study, the axial load ratio, n_y, and the slenderness ratio, λ_c, are defined by Eqs. (12) and (2), respectively.

$$n_y = N / N_0 \qquad (N_0 = {}_sA \cdot {}_s\sigma_y + {}_cA \cdot {}_c\sigma_B) \tag{12}$$

In Eq. (12), ${}_sA$ is the cross-sectional area of the steel tube, ${}_s\sigma_y$ is the yield stress of the steel tube and ${}_cA$ is the cross-sectional area of the concrete portion.

The value of α is set to 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3. Considering the limit value of the axial load ratio, n_y, shown in Table 1, it is set from about 0.05 to 0.8. The slenderness ratio, λ_c, corresponding to the axial load ratio, n_y, and the value, α, is calculated by Eq. (11). The slenderness ratio, λ_c, is less than or equal to 2.

In consideration of width-thickness ratio where the influence of local buckling is small, the size of cross section of square steel tube is 250mm and wall thickness of the steel tube is set to 12mm (See Figure 1). Yield stress of steel tube, ${}_s\sigma_y$, is 325N/mm^2 and compressive strength of concrete, ${}_c\sigma_B$, is 60N/mm^2.

3 RESULTS OF ANALYSIS AND DISCUSSION

3.1 Relationship between Bending Moment and Rotational Angle

Relationships between bending moment and rotational angle are shown in Figure 3. The bending moment, M_1, is normalized by the full plastic moment, M_{pc}, considering axial compressive force and the rotational angle, θ_1, is normalized by the elastic rotational angle θ_{pc}. Figure 3 shows the results when the axial load ratio, n_y, is equal to 0.1, 0.25, 0.5 and 0.75. The left, center and right figures show the case of α =0.05, 0.1 and 0.25, respectively. In Figure 3, the black circle shows the maximum bending strength, the white triangle shows the point where the steel tube yielded in the compressive area, the white circle shows the point where the steel tube yielded in the tensile area and the black triangle shows the point where the stress of the concrete reaches compressive strength. Moreover, the values next to marks show the axial load ratio.

According to these figures, as the axial load ratio increases, it is observed that the steel tube reaches the compressive yield stress in a smaller bending moment. When the axial load ratio, n_y, is equal to 0.1 and 0.25, the steel tube reaches the tensile yield stress before the stress of the concrete reaches the compressive strength and when the axial load ratio, n_y, is equal to 0.5 and 0.75, the stress of the concrete reaches the compressive strength before the steel tube reaches the tensile yield stress. The maximum bending strength could not be obtained when the axial load ratio, n_y, is equal to 0.1, 0.25 and 0.5 in the left figure, however the value of M_1 almost reach the full plastic moment. In the left and center figures, when the axial load ratio, n_y, is equal to 0.75, the CFT column reaches maximum bending strength without the steel tube reaching the tensile yield stress.

In the right figure, when the axial load ratio, n_y, is equal to 0.5, the CFT column reaches maximum bending strength without the steel tube reaching the tensile yield stress and when the axial load ratio, n_y, is equal to 0.75, the CFT column reaches maximum bending strength without the steel tube reaching the tensile yield stress and the stress of the concrete reaching the compressive strength. When the axial load ratio, n_y, is equal to 0.1, the CFT column reaches maximum bending strength without the stress of the concrete reaching the compressive strength.

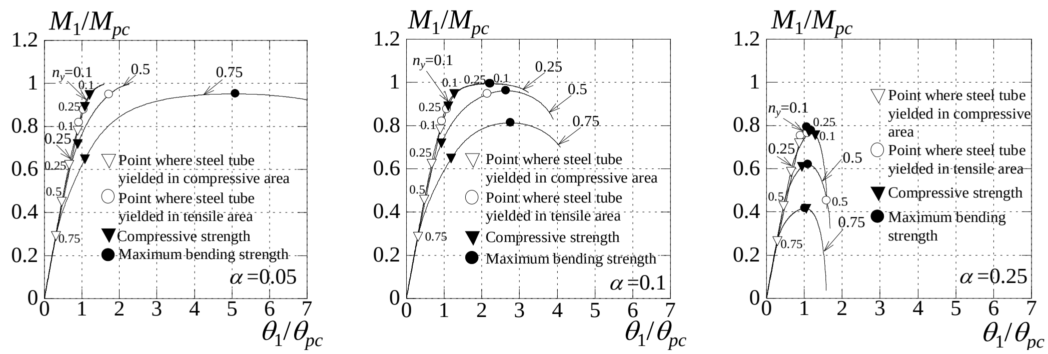


Figure 3. Relationship between bending moment and rotational angle.

3.2 Relationship between Maximum Bending Strength and Axial Load Ratio

Relationship between maximum bending strength and axial load ratio is shown in Figure 4. In Figure 4, the straight line shows the value of $M_{1\max}/M_{pc}$=0.95. When the value of α is equal to 0.05, the maximum bending strength, $M_{1\max}$, reach 95% of the full plastic moment, M_{pc}, under the condition that the axial load ratio, n_y, is less than or equal to 0.75. When the value of α is equal to 0.1, the maximum bending strength, $M_{1\max}$, reach 95% of the full plastic moment, M_{pc}, under the condition that the axial load ratio, n_y, is less than or equal to 0.5.

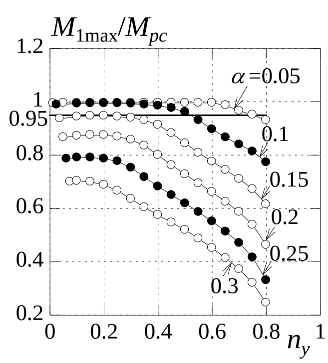


Figure 4. Relationship between maximum bending strength and axial load ratio.

3.3 Relationship between Effective Length to Section Depth Ratio and Axial Load Ratio

Relationship between the effective length to the section depth ratio and the axial load ratio is shown in Figure 5. In Figure 5, the straight line of l_k/D =30 shows the limit of the maximum effective length, l_k (=l_c), for CFT beam-columns. The straight lines of l_k/D =4 and 12 show the boundary between short columns, intermediate columns and slender columns. The white circles show the maximum bending strength, $M_{1\max}$, which reach 95% of the full plastic moment, M_{pc}, and the black circles show the maximum bending strength, $M_{1\max}$, which reach 90% of the full plastic moment M_{pc}.

The slenderness ratio, λ_c, is approximately one at l_k/D =30. In the case of α =0.05 and 0.1, the maximum bending strength, $M_{1\max}$, reach 95% of the full plastic moment, M_{pc}, even for CFT columns exceeding l_k/D =30. The value of α is the appropriate index for strength evaluation of CFT beam-columns because it is clear the maximum bending strength, $M_{1\max}$, reach 95% and 90% of the full plastic moment, M_{pc}, in Figure 5.

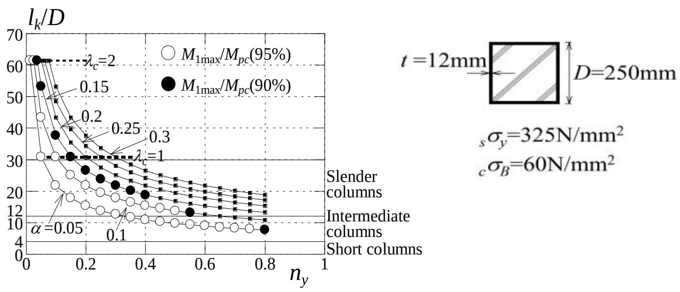


Figure 5. Relationship between effective length to section depth ratio and axial load ratio.

4 CONCLUSIONS

The conclusions derived from this study are as follows:

1) When the value of α is equal to 0.05, the maximum bending strength, $M_{1\max}$, reach 95% of the full plastic moment under the condition that the axial load ratio is less than or equal to 0.75. When the value of α is equal to 0.1, the maximum bending strength, $M_{1\max}$, reach 95% of the full plastic moment, M_{pc}, under the condition that the axial load ratio is less than or equal to 0.5.

2) The slenderness ratio, λ_c, is approximately one at l_k/D =30. In the case of α =0.05 and 0.1, the maximum bending strength, $M_{1\max}$, reach 95% of the full plastic moment, M_{pc}, even for CFT columns exceeding l_k/D =30.

3) The value of α (=$n_y\,\lambda_c^2$) is the appropriate index for strength evaluation of CFT beam-columns.

Acknowledgments

This study was supported by the Grant-in-Aid for Scientific Research of Japan Society for the Promotion of Science.

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