

STRESS STATE OF STEEL TUBE OF SQUARE CFT COLUMNS WHICH REACHED SHORT-TERM ALLOWABLE STRENGTH

MAO LIU¹, RYO HANDA², MASAE KIDO², and KEIGO TSUDA²

¹*Dept of Civil Engineering and Architecture, National Institute of Technology,
Tokuyama College, Shunan, Japan*

²*Dept of Architecture, The University of Kitakyushu, Kitakyushu, Japan*

The allowable strength was compared with the yield strength of CFT short columns subjected to constant axial force and horizontal force in previous studies. The yield strength of CFT columns is determined by 2/3 of compressive force of concrete in most cases. And the yield strength of CFT columns is smaller than the allowable strength. However, as an important index representing the damage state of CFT column, the stress state of steel tube when the CFT column reaches the short-term allowable strength is not clarified. The objective of this study is to make clear whether the steel tube yielded when the short-term allowable strength of square CFT column is reached by an analytical method. The analytical parameters are the effective length to depth ratio, axial force ratio and width to thickness ratio. The range of parameters in the cases which the steel tubes yield before the CFT columns reaches the allowable strength are shown and the decrease of stiffness in these cases are discussed.

Keywords: Steel concrete composite structure, Beam-column, Damage conditions, Length-to-width ratio, Width-to-thickness ratio, Initial stiffness.

1 INTRODUCTION

As a current type of structure, the concrete filled steel tube columns (CFT columns for short) are widely used especially for the high-rise buildings. In Japan, the Recommendations for Design and Construction of Concrete Filled Steel Tubular Structures (CFT Recommendations for short) published by Architectural Institute of Japan is one of the standards that show principles and design methods for CFT members (AIJ 2008). According to CFT Recommendations, the yield strength of CFT column should be determined by the smallest value among the compressive yield strength of steel tube, the tensile yield strength of steel tube and 2/3 of the compressive strength of concrete. However, it is cumbersome in calculation. For the allowable design method that bases on the limit state of safety and serviceability when the materials are elastic, the yield strength of CFT column is calculated by adding the strengths of concrete column and steel tube.

In the previous studies (Liu *et al.* 2011, Miyazaki *et al.* 2014), we have shown the relation between the short-term allowable strength (Short-term means the effects of occasional loads such as earthquake and wind are considered.) and the yield strength of CFT column, as well as the relationship with rotational angles. According to the relation of horizontal force and rotational angle, the stiffness of CFT column doesn't decrease sharply as soon as the yield strength is reached. Because whether the yield strength of CFT column is early reached or not depends on

axial force ratio, the design method using the yield strength as a short-term allowable strength is considered too safe in some cases. There are no studies to clarify the stress state of steel tube when the yield strength of CFT column reaches the short-term allowable strength. Therefore, as an important index representing damage state of CFT column, it is necessary to clarify whether the steel tube yielded when the strength of CFT column reaches the short-term allowable strength.

The purpose of this paper is to analyze the relation between horizontal force and horizontal deflection when a square CFT member is subjected to constant axial force and horizontal force, and to clarify whether the steel tube yielded before the strength of CFT member reaches the short-term allowable strength. Length-to-width ratio l_k/D (l_k is the buckling length and D is the width of cross-section.), axial force ratio n and width-to-thickness ratio D/t (t is the thickness of steel tube.) are chosen as parameters for analysis, and the ranges of these parameters when the steel tube yielded before the strength of CFT column reaches the short-term allowable strength are investigated. In addition, the tangential stiffness corresponding to the yield strength of steel tube and the short-term allowable strength is calculated respectively to evaluate the decrease of stiffness.

2 ANALYSIS

2.1 Analytical Model and Loading Conditions

As shown in Figure 1(a), a constant axial force N and a horizontal force H act on a cantilever CFT member whose length is L . The cross section of CFT member is a square. The width and the thickness of steel tube are D and t shown in Figure 1(b).

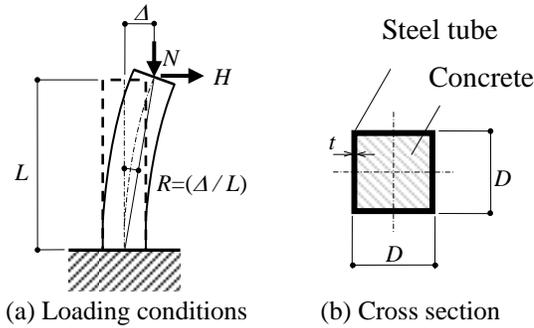


Figure 1. Analytical model.

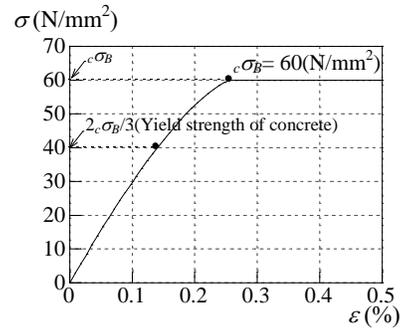


Figure 2. Stress-strain relation for concrete.

2.2 Analytical Method

The relation between horizontal force and rotational angle is obtained by the Column Deflection Curve method (CDC method for short) which is shown in CFT Recommendations. Firstly, the relation between bending moment M and curvature ϕ is calculated under the assumptions that the cross section does not change after deformation and the deflection is quite small. Then, based on the $M-\phi$ relationship, the relation between horizontal force H and rotational angle R is obtained. The second-order effects are considered in the calculation of CDC method.

2.3 Stress-Strain Relations

The stress-strain relation of concrete is calculated by Eq. (1) which is presented in State-of-the-Art Report on High-Strength Concrete edited by AIJ (2009). The stress-strain model of Fafitis

and Shah is used. However, the strength is set to be constant to equal $c\sigma_B$ if the strength σ is over the compressive strength of concrete $c\sigma_B$.

$$\sigma = \begin{cases} \left\{ 1 - \left(1 - \frac{\varepsilon}{\varepsilon_m} \right)^a \right\} c\sigma_B & (\varepsilon < \varepsilon_m) \\ \sigma = c\sigma_B & (\varepsilon \geq \varepsilon_m) \end{cases} \quad (1)$$

In which $a = \frac{E_c \cdot \varepsilon_m}{c\sigma_B}$ and $\varepsilon_m = 0.93 \cdot c\sigma_B^{1/4} \cdot 10^{-3}$.

The elastic modulus of concrete E_c is calculated by Eq. (2).

$$E_c = (3.32 \times \sqrt{c\sigma_B} + 6.9) \times 10^3 \quad (2)$$

In which, $c\sigma_B$ is the compressive strength of concrete.

The tensile strength of concrete is ignored in this study. The stress-strain relation of concrete is shown as Figure 2. The stress-strain relation of steel tube is assumed to be elastic-perfectly plastic model. The elastic modulus of steel tube is equal to $2.05 \times 10^5 \text{N/mm}^2$.

2.4 Short-Term Allowable Strength

In the CFT recommendations, the CFT members with different lengths are divided into three kinds for structural design, short column (i.e., $l_k/D \leq 4$), intermediate column (i.e., $4 < l_k/D \leq 12$) and slender column (i.e., $l_k/D > 12$). The design equations are different by the kinds of CFT members. The short-term allowable strength of CFT members which is subjected to axial force and bending moment is calculated by adding the strengths of concrete column and steel tube. For short column, second-order effects are ignored in the calculation of allowable strength.

2.5 Horizontal Force H_1 Corresponding to Short-Term Allowable Strength

In this paper, we define the horizontal force when the first-order moment ($H \times L$) of CFT column is equal to short-term allowable strength M_a as H_1 , and the rotational angle is R_1 corresponding to H_1 . Figure 3 shows the relation between horizontal force H and rotational angle R . The value of H_1 is marked by \bullet in this figure.

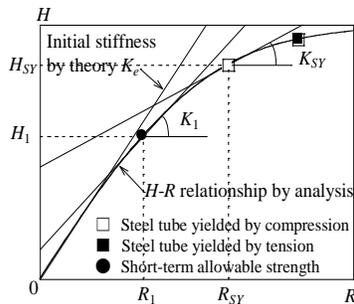


Figure 3. Relation of H - R .

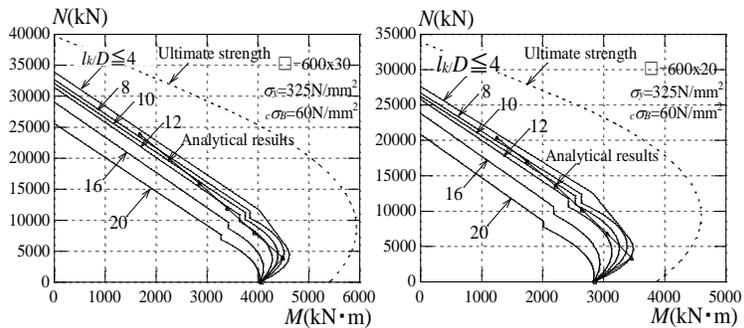


Figure 4. Relation of M - N with different l_k/D .

2.6 Horizontal Force H_{SY} Corresponding to Yield Strength of Steel Tube

The bending moment when the steel tube yielded by compression or tension (i.e., the stress of the edge of cross-section equals the yield stress of material σ_y) is obtained from the $M-\phi$ relationship. Then, making the bending moment at the bottom of CFT column equal to this value, the horizontal force in this situation is obtained from the $H-R$ relationship. In Figure 3, the points when the steel tube yielded by compression and tension are marked respectively by \square and \blacksquare . The smaller one of \square and \blacksquare is defined as the horizontal force H_{SY} . The rotational angle corresponding to H_{SY} is named as R_{SY} . According to Figure 3, because the value of H corresponding to \square is smaller than that corresponding to \blacksquare , the horizontal force H_{SY} is determined by the compressive yielding.

Figure 4 shows the short-term allowable strength mentioned in Section 2.4 by $M-N$ relationship. The bending moment for short column (i.e., $l_k/D \leq 4$) when steel tube yielded obtained by analysis is shown by \blacktriangle . According to this figure, it is understood that the values by analysis are almost smaller than the values of short-term allowable strength.

3 RESULTS AND DISCUSSION

3.1 Analytical Parameters

The parameters used in this paper are shown as follows.

- (i) Length-to-width ratio l_k/D : 4, 8, 10, 12, 16, 20
- (ii) Axial force ratio $n=N/N_0$ ($N_0= A\sigma_y+cA_c\sigma_B$): 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6
- (iii) Width-to-thickness ratio D/t : 20, 30

The width of cross-section D is set to equal 600mm. The compressive strength of concrete $c\sigma_B$ and the yield strength of steel σ_y is 60N/mm^2 and 325N/mm^2 respectively.

3.2 Comparison of H_1 and H_{SY}

Figure 5 shows the relation between the axial force ratio n and the value of H_{SY}/H_1 obtained by analysis, with the length-to-width ratio l_k/D as a parameter. When the value of H_{SY}/H_1 is smaller than unity, the steel tube yielded before the short-term allowable strength is reached. Table 1 shows the data used in Figure 5. The range of $H_{SY}/H_1 < 1$ is enclosed with bold line. Except the cases of $n=0$ and $n=0.1$ of $D/t=30$, the yield strength of steel tube is determined by compressive yield strength.

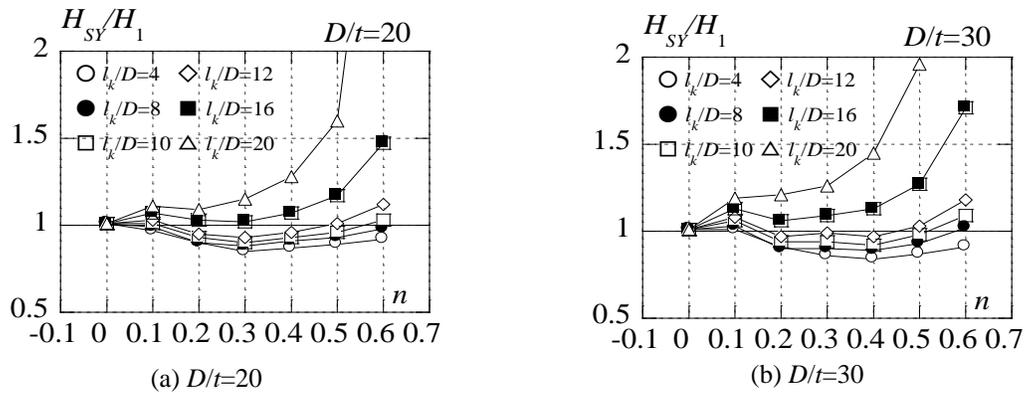


Figure 5. Values of H_{SY}/H_1 .

According to Figure 5, the value of H_{SY}/H_1 increases as the length-to-width l_k/D increases. This is probably because the short-term allowable strength decreases as the value of l_k/D increases. In cases of $l_k/D = 16$ and 20, the value of H_{SY}/H_1 is larger than unity whatever the axial force ratio n is. It is understood that steel tube doesn't yield in case of slender column ($l_k/D > 12$) when the short-term allowable strength of CFT member is reached. In addition, when the length-to-width l_k/D equals 12 or less, the smallest value of H_{SY}/H_1 appears in case of $n=0.3$ or 0.4.

Table 1. (a) Values of H_{SY}/H_1 when $D/t=20$.

n	l_k/D					
	4	8	10	12	16	20
0	1.01	1.01	1.01	1.01	1.01	1.01
0.1	0.97	0.99	1.01	1.03	1.07	1.11
0.2	0.90	0.90	0.93	0.95	1.03	1.09
0.3	0.85	0.88	0.90	0.93	1.02	1.15
0.4	0.87	0.91	0.93	0.96	1.07	1.28
0.5	0.89	0.93	0.96	1.01	1.17	1.60
0.6	0.92	0.98	1.03	1.12	1.47	3.57

Table 1. (b) Values of H_{SY}/H_1 when $D/t=30$.

n	l_k/D					
	4	8	10	12	16	20
0	1.01	1.01	1.01	1.01	1.01	1.01
0.1	1.01	1.03	1.06	1.08	1.13	1.19
0.2	0.91	0.90	0.94	0.97	1.06	1.21
0.3	0.86	0.90	0.94	0.99	1.09	1.26
0.4	0.84	0.89	0.92	0.97	1.13	1.45
0.5	0.87	0.93	0.98	1.03	1.27	1.96
0.6	0.91	1.02	1.09	1.18	1.71	9.82

Table 2. (a) Values of R_{SY}/R_1 ($l_k/D=10, D/t=20$).

n	$R_{SY}(\%)$	$R_1(\%)$	R_{SY}/R_1	H_{SY}/H_1
0	0.478	0.473	1.01	1.01
0.1	0.509	0.503	1.01	1.01
0.2	0.428	0.466	0.92	0.93
0.3	0.359	0.402	0.89	0.90
0.4	0.300	0.322	0.93	0.93
0.5	0.241	0.248	0.97	0.97
0.6	0.181	0.172	1.05	1.05

Table 2. (b) Values of R_{SY}/R_1 ($l_k/D=10, D/t=30$).

n	$R_{SY}(\%)$	$R_1(\%)$	R_{SY}/R_1	H_{SY}/H_1
0	0.455	0.450	1.01	1.01
0.1	0.517	0.486	1.06	1.06
0.2	0.428	0.462	0.93	0.94
0.3	0.352	0.378	0.93	0.94
0.4	0.293	0.319	0.92	0.92
0.5	0.234	0.240	0.98	0.98
0.6	0.171	0.158	1.09	1.09

3.3 Comparison on Rotational Angle

The rotational angles R_{SY} and R_1 corresponding to H_{SY} and H_1 are shown in Tables 1 and 2. According to Table 2, the difference between the values of R_{SY}/R_1 and the values of H_{SY}/H_1 shown in Section 3.2 is almost 0, i.e., the values of H_{SY}/H_a and R_{SY}/R_1 are almost the same.

3.4 Decrease of Stiffness

In this section, the decrease of stiffness when the steel tube yielded before the short-term allowable strength is reached is discussed. K_{SY} and K_1 represent the tangential stiffness corresponding to H_{SY} and H_1 , and the values of K_{SY} and K_1 are obtained by the relation of $H-R$ like Figure 3. The initial stiffness by theory K_e is calculated by Eq. (3).

$$K_e = \frac{H}{R} = \frac{ZN}{\tan Z - Z} \quad (3)$$

in which $Z = L\sqrt{N/EI}$ and $EI = E_c I_c + E_s I_s$.

The comparison of the initial stiffness K_e to the stiffness K_{SY} and K_1 is presented in Figure 6. The values of K_{SY}/K_e and K_1/K_e are shown with dotted lines and solid lines respectively. According to

Figure 6, the value of K_{SY}/K_e is 0.77 to 0.97, which is almost the same regardless of the value of l_k/D . In regard to the effect of width-to-thickness ratio, the value of K_{SY}/K_e with the same axial force ratio is smaller when the width-to-thickness ratio is larger. On the decrease of stiffness when the allowable strength is reached, when the value of l_k/D is smaller, the value of K_1/K_e decreases at a larger rate in most cases. Comparing the values of K_{SY}/K_e and K_1/K_e , the maximum difference is 0.214 which appears in the case when $l_k/D=4$ and $n=0.4$ in Figure 6(a), i.e., after the steel tube yielded, the stiffness of CFT column decreases by about 21% until the short-term allowable strength is reached.

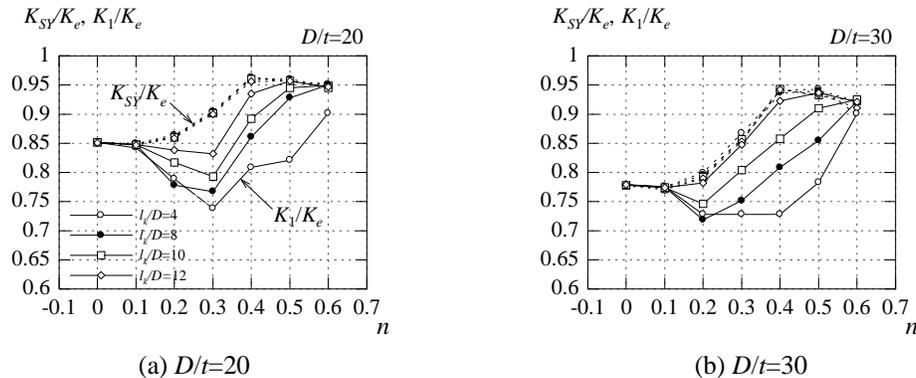


Figure 6. Decrease of stiffness.

4 CONCLUSIONS

In this paper, the relation between horizontal force and deflection when a square CFT member is subjected to constant axial force and horizontal force is shown by analytical method. The horizontal force H_{SY} and rotational angle R_{SY} when the steel tube yielded are compared with the lateral load H_1 and rotational angle R_1 when the short-term allowable strength is reached by taking length-to-width ratio l_k/D , axial force ratio n and width-to-thickness ratio D/t as parameters. The main findings are shown as follows.

- (i) The ranges of these parameters when the steel tube yielded before the CFT column reaches the short-term allowable strength are investigated. According to Figure 5, the value of H_{SY}/H_1 increases as the length-to-width l_k/D increases. The steel tube doesn't yield in the case of slender column ($l_k/D > 12$) when the short-term allowable strength of CFT member is reached.
- (ii) According to Table 2, the values of H_{SY}/H_1 and R_{SY}/R_1 are almost the same.
- (iii) Comparing the values of K_{SY}/K_e and K_1/K_e , the stiffness of CFT column decreases by about 21% until the short-term allowable strength is reached.

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