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Research on the Calculation Method of Skeleton Curve of Variable Cross Sectional Concrete Filled Steel Tubular Laced Columns with Flat Lacing Tube

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***Abstract*—Variable cross-sectional Concrete Filled Steel Tubular (CFST) laced column with flat lacing tube is a kind of emerging combination column; it has broad application prospects in high pier bridges and high-rise buildings. The finite element analysis method of CFST laced columns is built with universal program of OpenSEES, and the influence of structural parameters on seismic performance of CFST laced columns is researched. Then the calculation method of skeleton curve of variable cross-sectional CFST laced columns is studied referencing the computing framework of hysteretic model of CFST single tube column and equal sectional laced column, the calculation formula of elastic stiffness, horizontal peak load and its displacement, fall-period stiffness are developed respectively. Engineering examples verifications of Gan haizi bridge's laced column pier are processed with OpenSEES program, and research results indicated that the calculated values are coincident well with numerical results. Finally a rational method to calculate the skeleton curve of variable cross-sectional CFST laced columns with flat lacing tube is provided on the basis of the analytical results.**

Keywords-variable cross-sectional; concrete filled steel tube column; flat lacing tube; skeleton curve; calculation method

I. INTRODUCTION

Concrete filled steel tubular (CFST) laced columns are widely used as building columns and as elements in arch bridges [1] [2]. Compare with equal sectional laced column, variable cross-sectional laced columns (the section size of column is gradually increasing from top to bottom) is advantageous in relatively high compressive strength, capacity, relatively high horizontal bearing capacity, good overall stability, excellent deformation capacity and attractive appearance. Furthermore, this type of hybrid column has more excellent earthquake resistance for its center of gravity is lower and the reaction of the column under earthquake function is decreased [3]. In recent years, variable cross-sectional laced columns with flat lacing tube was found to be applied in high-pier bridges located in strong earthquake region, and it has become one of the most potential pier forms. For example, combination column of this type was used in Ganhaizi super large bridge in Sichuan province, the largest laced column pier is 67.29 meters high.

Skeleton curve is a key quota to study the seismic behavior of concrete filled steel tubular columns, and it is also an important basis to determine the characteristic points of the restoring force model. In recent years, many research work on skeleton curve of CFST single-tube column have been carried out and effective algorithms are proposed[4]. Meanwhile, some experimental study on hysteretic behavior of equal sectional laced column have been done (including two-element and four-element type), and the corresponding calculation formula of skeleton curve has been proposed on the base of finite element analysis results [5]-[8]. However, seldom research has been conducted on aseismic behavior of variable cross-sectional CFST laced columns, and there is an urgent need of calculation method on skeleton curve.

In this paper, a parametric study of the seismic performance of variable cross-sectional CFST laced columns by using the OpenSEES finite-element analysis program was performed. On the basis of the findings, the calculation methods of key parameters of skeleton curve are discussed. Finally a universal method that can accurately predict the skeleton curve of four-tube variable cross-sectional CFST laced columns with flat lacing tube is proposed by reference to calculation formula of CFST single tube column and same cross-sectional laced columns.

II. FINITE ELEMENT ANALYSIS OF SEISMIC BEHAVIOR

A parametric study of the seismic performance of variable cross-sectional CFST laced columns by using the OpenSEES finite-element analysis program was performed referencing the modeling method in Refs, 8.

Fiber element method is adopted in finite element modeling, and element type is dispBeamColumn element. The effect of P-Delta should be taken into account in local direction coordinates of members. The bottom of laced column keeps consolidation, and displacement control method is used to simulate quasi-static loading test.

Standard specimen is named BP-0(shown in Fig.1), it is modeled as Ganhaizi super bridge and the scale is 1:10. The height of column is 2.5m, the slope of longitudinal element is 1:40, and axial compression ratio is 0.15. Elastic modulus of steel and concrete is 2.06×10^5Mpa, and 3.45×10^4MPa, respectively. Specified yield strength of steel=345MPa and compressive strength of concrete=38MPa. More information about the nonlinear material properties used in this study can be found in Refs, 4 and Refs, 9.

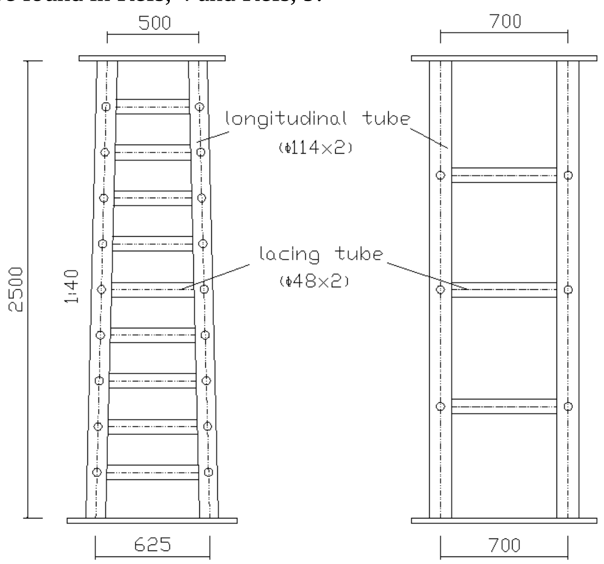

Figure 1. Configuration of specimen BP-0 (unit:mm)

The variation range of parameters of 44 specimens are presented as follows: the slope of longitudinal element is varied from 1:70 to 1:20, axial compression ratio is varied from 0.1 to 0.5, the length of column is varied from 2.5m to 15m, vertical spacing of flat lacing tubes is varied from 0.125 to 0.5m, steel ratio of longitudinal element is varied from 4% to 19%, diameter ratio of lacing tubes and longitudinal tubes is varied from 0.2 to 0.8, yield strength of steel is varied from 240Mpa to480Mpa, concrete label is varied from C30 to C70.

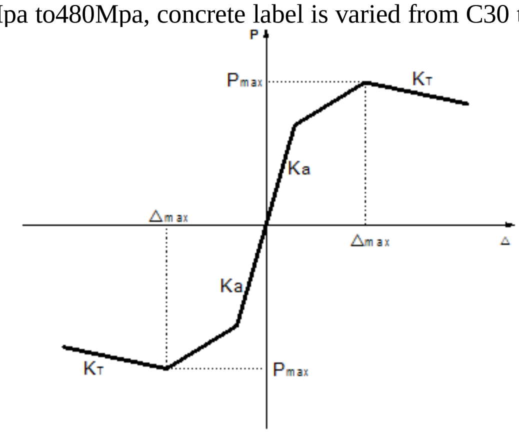

Figure 2. Key parameter of typical skeleton curve

Through the numerical calculation of these specimens, typical skeleton curve is obtained in Fig.2. Here, K_a is elastic stiffness, P_{max} is horizontal peak load, Δ_{max} is displacement on peak load, K_T is fall-period stiffness. Then the influence rules of parameters on skeleton curve of laced columns are researched, shown in Tab.1.

TABLE I. KEY PARAMETERS ON SKELETON CURVE OF CFST LACED COLUMN

Parameter	K_a	P_{max}	Δ_{max}	K_T
Slope of longitudinal element↗	↗	↗	—	↗
Axial compression ratio↗	—	↘	↘	↗
Length of laced column↗	↘	↘	↗	↘
Vertical spacing of lacing tubes↗	↘	↘	—	—
Diameter ratio of tubes↗	↗	↗	—	↗
Steel ratio↗	↗	↗	—	↗
Concrete strength↗	—	↗	—	—
Yield strength of steel↗	—	↗	—	—

III. CALCULATION OF CHARACTERISTIC VALUE OF SKELETON CURVE

Comparing the numerical results and research results in Refs, 4 through Refs, 8, it can be found that the influence rule of main parameters on CFST column is similar. So the calculation method of skeleton curve of variable cross-sectional CFST laced columns will be studied referencing the computing framework of hysteretic model of CFST single tube column and equal sectional laced column.

A. *Elastic Stiffness (K_a)*

The elastic stiffness of CFST single tube column can be calculated as Eq.1 [4].

$$K_a = \frac{3K_e}{(L_0)^3} = \frac{3(E_sI_s + 0.6E_cI_c)}{(L_0)^3} \tag{1}$$

Where K_a is elastic stiffness, K_e is elastic stiffness Flexural rigidity, L0 is the length of CFST single tube column, E_s and E_c are Elastic modulus of steel and concrete, I_s and I_c are Moment of inertia of longitudinal steel tube and core concrete, respectively.

It is suggested that Eq.1 can be rewritten into Eq.2 in the calculation of elastic stiffness (K_a) of variable cross-sectional CFST laced columns with flat lacing tube. Here, g denotes equivalent length factor (which can be obtained by Eq.3 and Eq.4 [10] [11]), and K denotes equivalent slenderness ratio factor (which can be obtained by Eq.5 and Eq.6). Firstly variable cross-sectional CFST laced column with the length of L will equivalent to equal sectional laced column with the length of gL (their top section is same), then equal sectional laced column can be equivalent to single tube column with the length of KgL.

$$K_a = \frac{3(E_s I_s + 0.6 E_c I_c)}{(gKL)^3} \quad (2)$$

$$g = 1 - 0.375\gamma + 0.08\gamma^2 (1 - 0.0775\gamma) \quad (3)$$

$$\gamma = (2 * \theta * L) / d_0 \quad (4)$$

$$K = \sqrt{1 + 6\mu} \quad (5)$$

$$\mu = \frac{1}{2}\left(\frac{b}{\mathrm{gL}}\right)^2 (3.83 \frac{A_d}{A_b}) \quad (6)$$

Where γ is section enlargement factor, K_e is flexural rigidity, θ is the slope of longitudinal element, d_0 is width of top section of laced column, μ is shear flexibility coefficient, b is plane center distance of longitudinal element, A_d and A_b are equivalent area of single longitudinal element and area of single flat lacing tube, respectively.

According to this method, the comparison of calculation values of elastic stiffness (K_a) and numerical values by OpenSEES program for 44 specimens are shown in Fig.3. It can be found that calculation results coincided very closely with the numerical results. The average ratio (calculated value/ numerical value) is 1.028.

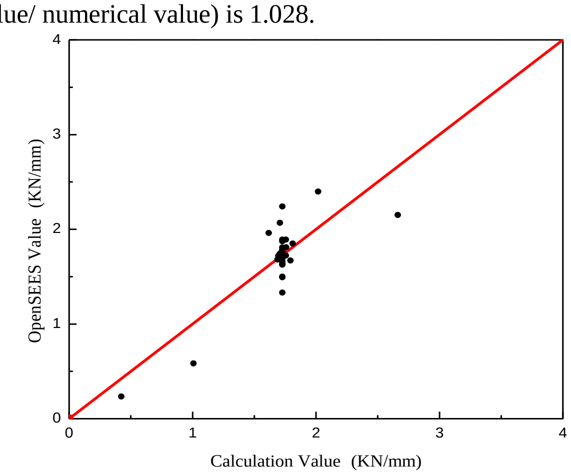

Figure 3. Comparison of K_a of CFST laced columns

B. *Horizontal Peak Load (P_{max})*

It is suggested that horizontal peak load (P_{max}) of variable cross-sectional CFST laced column can be calculated by Eq.7, referring to the formula of CFST equal sectional laced column [8] and single tube column [4].

$$P_{\max} = \sqrt{(1 - n^2)}\,\frac{M_0}{2\mathrm{g}L} \quad \textbf{(7)}$$

Where n is axial compression ratio, M_0 is Moment bearing capacity, g is equivalent length factor, and L is the length of laced column. M_0 can be obtained by using Eq.8 to Eq.11.

$$M_0 = (\gamma_m W_{scm} f_{scy}) \quad (8)$$

$$\gamma_m = 1.04 + 0.48\ln(\xi + 0.1) \quad (9)$$

$$W_{scm} = (A_s + A_c) \times r \times 4 \quad (10)$$

$$f_{scy} = \frac{N_0}{S} = \frac{N_0}{b \times c} \quad (11)$$

Where γ_m is coefficient of bending strength, ξ is Hoop factor, W_{scm} is section bending modulus, A_s and A_c are area of longitudinal tube and concrete, respectively, r is turning radius of laced column, f_{scy} is coefficient of composite compressive strength, N_0 is ultimate load of laced column , b and c are center distance of longitudinal element in plane and out of plane, respectively.

In order to verify this method, comparison of calculation values of horizontal peak load (P_{max}) and numerical values by OpenSEES program for 44 specimens are shown in Fig.4. It can be found that calculation results coincided well with the numerical results. The average ratio (calculated value/ numerical value) is 0.990.

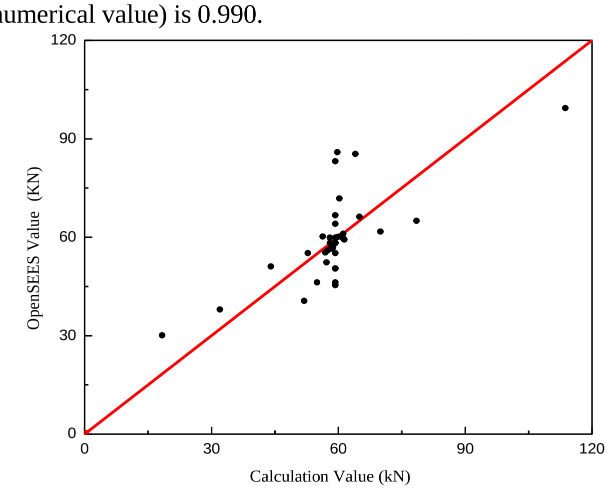

Figure 4. Comparison of $P_{\max}$ of CFST laced columns

C. Displacement at Peak Load (Δ_{max})

According to Tab.1, it can be found that axial compression ratio (n), the length of column (L) and yield strength of steel are key parameters which have important influence on displacement at peak load (Δ_{max}). This rule is similar to CFST single tube column. So it is suggested that Δ_{max} of variable cross-sectional CFST laced column can be calculated by Eq.12, referring to the formula of CFST single tube column [4].

$$\Delta_{\max} = K_p \cdot \frac{P_{\max}}{K_a} \qquad (12)$$

Where K_p =amplification factor of peak displacement, it is relate to three parameters mentioned earlier and can be expressed by using Eq.13. Here, λ^* is equivalent slenderness, it can be obtained by Eq.14.

$$K_p = (2.8 - n - 0.03 \times \lambda^*) \times \left(\frac{345}{f_y} \right) \qquad (13)$$

$$\lambda^* = gK\lambda \qquad (14)$$

According to this method, the comparison of calculation values of peak displacement (Δ_{max}) and numerical values by OpenSEES program for 44 specimens are shown in Fig.5. It can be found that calculation results coincided well with the numerical results. The average ratio (calculated value/ numerical value) is 1.090.

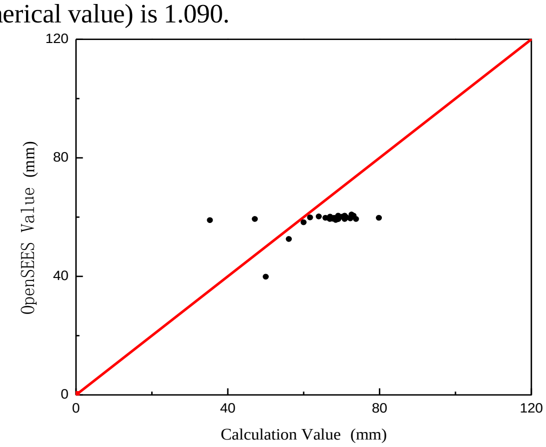

Figure 5. Comparison of $\Delta_{\max}$ of CFST laced columns

D. Fall-period Stiffness (K_T)

Numerical analysis indicated that the main parameters which have a certain influence on the fall-period stiffness (K_T) of variable cross-sectional CFST laced column's skeleton curve are n, λ^* and fy. This rule is similar to CFST single tube column. Therefore, K_T can be calculated by Eq.15, referring to the formula of CFST single tube column [4].

$$K_T = \frac{-9.83 f(n) \lambda^{*0.75} f_y}{E_s \xi} K_a \qquad (15)$$

According to research findings on parameter analysis, it is indicated that fall-period stiffness (K_T) will increase gradually with the increase of axial compression ratio (n) when n is lower than 0.4, and when n is larger than 0.4, the effect of n on K_T is relatively small. So the value of f (n) can be calculated by using Eq.16 depending on the scope of n.

$$f(n) = \begin{cases} n + 0.35 & (n \le 0.4) \\ 1 & (n > 0.4) \end{cases} \qquad (16)$$

According to this method, the comparison of calculation values of fall-period stiffness (K_T) and numerical values by OpenSEES program for 44 specimens are shown in Fig.6. It can be found that calculation results coincided well with the numerical results. The average ratio (calculated value/ numerical value) is 0.90.

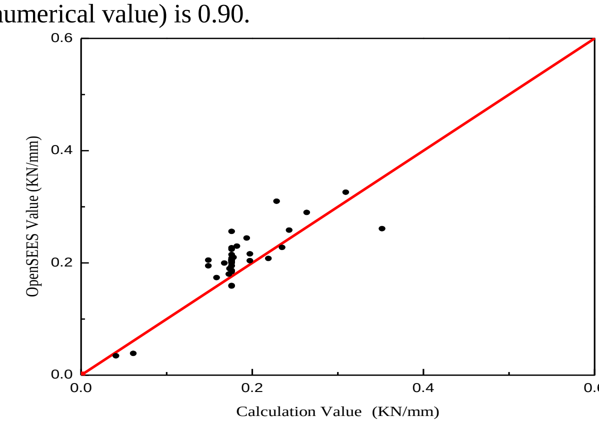

Figure 6. Comparison of K_T of CFST laced columns

IV. CALCULATION METHOD VALIDATION

In order to verify the rationality of calculation method of skeleton curve in this paper, pier 2 of Ganhaizi Bridge in Yaxi expressway was chosen as research object. Pier 2 is four-element variable cross-sectional CFST laced column with flat lacing tube, and three steel pipe trusses are placed between longitudinal elements in bridge width direction to strengthen the whole stiffeners of piers.

The height of this laced column is 24m, the slope of longitudinal element is 1:50, and axial compression ratio is 0.15. Plane center distance of longitudinal element is 1.15m at top section, and the distance at bottom section is 2.11m. Center distance of longitudinal element out of plane is 12.25m. Vertical spacing of flat lacing tube is 2m. Outside diameter and thickness of longitudinal tube are 813mm and 12mm, respectively. Outside diameter and thickness of lacing tube are 406mm and 10mm, respectively. The elastic modulus of steel and concrete is 2.06×10^5Mpa and 3.45×10^4MPa, respectively. Specified yield strength of steel=345MPa, and compressive strength of concrete=38MPa.

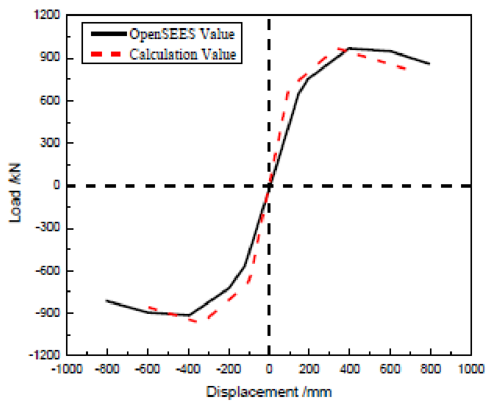

Figure 7. Comparison of skeleton curves

The comparison of skeleton curve calculated by the method in this paper and by OpenSEES program for Pier 2 is shown in Fig.7. It can be found from Fig.7 that two skeleton curves are very close, that is, calculation results coincided well with the numerical results. So this calculation method on skeleton curve is verified to be reasonable for variable cross-sectional CFST laced column with flat lacing tube.

V. CONCLUSIONS

In this analytical investigation, four-tube variable cross-sectional CFST laced column whit flat lacing tube was investigated and recommendations are provided to calculate the skeleton curve. On the basis of these results, the following general conclusions were obtained:

- A finite-element modeling scheme was used to perform a parametric study. Then the influence rule of parameters on the skeleton curve was obtained. This rule is similar with CFST single tube column and equal sectional laced column.
- According the finding of parametric study, formula of key parameters on skeleton curve is proposed referencing the CFST single tube column and equal sectional laced column.
- Finally a practical method to calculate the skeleton curve of variable cross-sectional CFST laced column with lacing tube was developed (shown in Tab.2) on the basis of the finite-element analysis and the engineering example verification.

TABLE II. CALCULATION METHOD OF SKELETON CURVE OF VARIABLE CROSS-SECTIONAL CFST LACED COLUMN WITH LACING TUBE

Parameter	Calculation formula
Elastic stiffness K_a	$K_a = \frac{3(E_sI_s + 0.6E_cI_c)}{(KgL)^3}$ $g = 1 - 0.375\gamma + 0.08\gamma^2(1 - 0.0775\gamma)$ $\gamma = (2 * \theta * L)/d_0$ $K = \sqrt{1 + 6\mu}$ $\mu = \frac{1}{2}\left(\frac{b}{gL}\right)^2(3.83\frac{A_c}{A_b})$
Horizontal peak load P_{max}	$P_{max} = \sqrt{(1 - n^2)}\frac{M_0}{2gL}$ $M_0 = \alpha\gamma_m W_{scm} f_{scy}$
peak displacement Δ_{max}	$\Delta_{max} = K_p \cdot \frac{P_{max}}{K_a}$ $K_p = (2.8 - n - 0.03\times\lambda^*)\times\left(\frac{345}{f_y}\right)$
fall-period stiffness K_T	$K_T = \frac{-9.83f(n)\lambda^{0.75}f_y}{E_s\xi}K_a$ $f(n) = \begin{cases} n + 0.35 & (n \le 0.4) \\ 1 & (n > 0.4) \end{cases}$

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