A Fiber Beam-Column Element for Circular Concrete Filled Steel Tube under Torsion

J.G. Nie, Y.H. Wang & J.S. Fan
Department of Civil Engineering, Tsinghua University, China

SUMMARY:
Based on appropriate geometrical, material constitutive and equilibrium equations, a new fiber beam-column element for circular concrete filled steel tubes under torsion was proposed, and a nonlinear analysis program was also developed for obtaining the entire loading history of concrete filled steel tube under combined compression-bending-torsion load could be predicted with good agreement with test results. High solution precision and efficiency could be obtained when analyzing the mechanical behavior of circular concrete filled steel tubes under combined compression-bending-torsion load.

Keywords: concrete filled steel tube, fiber beam-column element, nonlinear analysis, torsion

1. INTRODUCTION

Concrete filled steel tube columns are frequently used for the piers of bridges due to the excellent mechanical properties (Shanmugam and Lakshmi, 2011). Curved bridges often exist due to the traffic line, and piers are often fixed connected to in order to ensure the integrity of curved bridges. Different from the straight bridges, the stiffness centre and the mass centre of the curved bridges do not locate at the same position, so the torsion effect will be created in the piers of curved bridges when horizontal earthquake happened. So the piers bear the compression-bending-torsion combined action.

The tests on concrete filled steel tubes members with circular section under pure static torsion have been carried out by Xu and Gong (1991), Beck and Kiyomiya (2003). Then Han et al. (2007) have used the three-dimensional refined finite element method to study the torsion behavior of concrete filled steel tube columns, and then the simplified design method was proposed by the regression analysis. Lee et al. (2009) have proposed a theoretical model for analyzing concrete filled steel tubes under pure static torsion with good agreement.

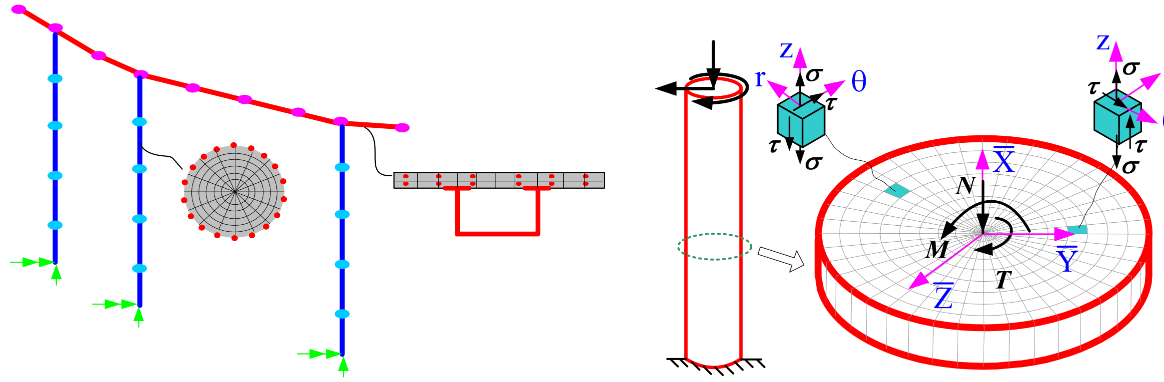

Figure 1.1 Fiber beam-column model considering torsion for steel-concrete composite curved girder bridges

The literatures available now have proved that the fiber beam-column model used for predicting the response of structures under earthquake has high solution efficiency and precision (Ambrisi and Filippou, 1999). However, when concrete filled steel tubes are subjected to torsion, the shear stress will be produced on the section, so the torsion effect can not be considered. In this paper, A new fiber beam-column element is developed based on the traditional fiber beam-column model in order to simulate the mechanical behavior of circular concrete filled steel tubes subjected to combined compression-bending-torsion load as shown in Figure1.1.

2. CONSTITUTIVE LAWS

The reference frame for the fiber beam-column element is the local coordinate system $\overline{X}, \overline{Y}, \overline{Z}$, while X,Y, Z denotes the global reference system. The longitudinal axis $\overline{X}$ is the union of geometric centroids of each section. There are totally six degrees for each node of the two node beam-column element considering torsion effect. Three concentrate force F_x, F_y, F_z and three moment M_x, M_y, M_z are included in the nodal generalized force components, and three displacement Δ_x, Δ_y, Δ_z and three rotation angle θ_x, θ_y, θ_z are included in the nodal generalized displacement components. Therefore, there are totally twelve components in the element generalized force vector $\mathbf{Q}_e$ and the element generalized displacement vector $\mathbf{q}_e$ of the fiber beam-column element respectively. The element stiffness matrix $\mathbf{K}_e$ is a 12×12 square matrix.

In the following parts, the element force vector $\mathbf{Q}_e$ and element stiffness matrix $\mathbf{K}_e$ in the global coordinate system will be calculated from the element displacement vector $\mathbf{q}_e$ through a serious decomposition and integrated processes.

2.1. Transformation from global coordinate system to local element coordinate system

According to the geometrical relations in the three dimensional space, the transformation matrix **V** between the global coordinate system and local element coordinate system can be obtained as:

$$\mathbf{V} = \begin{bmatrix} \mathbf{R}_{3\times3} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{R}_{3\times3} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{R}_{3\times3} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{R}_{3\times3} \end{bmatrix} \tag{2.1}$$

The transformation matrix **V** is a 12×12 block square matrix composed by four 3x3 square matrixes, which can be calculated as:

$$R_{3\times3} = \left\{ \frac{\vec{x}_e}{\|\vec{x}_e\|_2}, \frac{\vec{y}_e}{\|\vec{y}_e\|_2}, \frac{\vec{z}_e}{\|\vec{z}_e\|_2} \right\}^{\mathrm{T}} \tag{2.2}$$

Where $\vec{\mathbf{x}}_e$ is the vector subtracted the coordinate (x_1, y_1, z_1) of node 1 from the coordinate (x_2, y_2, z_2) of node 2, $\vec{\mathbf{y}}_e$ is the vector perpendicular to the axis, $\vec{\mathbf{z}}_e$ is the cross product of $\vec{\mathbf{x}}_e$ and $\vec{\mathbf{y}}_e$.

Then the element generalized displacement in the local element coordinate system can be calculated as the product of the transformation matrix and the element generalized displacement in the global coordinate system:

$$\overline{\mathbf{q}}_e = \mathbf{V} \bullet \mathbf{q}_e \tag{2.3}$$

2.2. Transformation from element displacement to section displacement at integration point

The linear shape function is chosen for the deformation field of the fiber beam-column element. The shape function matrix for calculating the section generalize displacement vector in the local element coordinate system can be directly obtained as:

$$\mathbf{N}(x) = [\mathbf{diag}\{\phi_1(x), \phi_1(x) \ldots \phi_1(x)\}_{6\times6},\ \ \mathbf{diag}\{\phi_2(x), \phi_2(x) \ldots \phi_2(x)\}_{6\times6}] \tag{2.4}$$

Where $\phi_1(x)=1-x/L$, $\phi_2(x)= x/L$, L is the length of the element。

Therefore, the section generalized displacement vector at integration points can be calculated as the product of the shape function matrix and the element generalized displacement vector:

$$\bar{\mathbf{q}}(x) = \mathbf{N}(x) \bullet \bar{\mathbf{q}}_e \tag{2.5}$$

2.3. Transformation from section displacement to section generalize strain

Based on the deformation compatibility principle, the section generalize strain vector $\mathbf{d}=\{\varepsilon_x\ \ \gamma_y\ \ \gamma_z\ \ \phi_x\ \ \phi_y\ \ \phi_z\ \}^{\mathbf{T}}$ can be obtained by differentiating the section generalized displacement along the longitudinal direction of the element:

$$\mathbf{d}(x) = \bar{\mathbf{q}}'(x) = \mathbf{N}'(x) \bullet \bar{\mathbf{q}}_e \tag{2.6}$$

2.4. Transformation from section generalize strain to strain of fibers

In the local element coordinate system, the section of the concrete filled steel tube is divided into fibers, including concrete fibers and steel fibers. The strain matrix **E** of all the fibers is defined as:

$$\mathbf{E} = \left[\mathbf{e}_1^{\mathbf{T}}\ \ \cdots\ \ \mathbf{e}_i^{\mathbf{T}}\ \ \cdots\ \ \mathbf{e}_n^{\mathbf{T}}\right]^{\mathbf{T}} \qquad \left(1 \le \mathbf{i} \le \mathbf{n},\ \mathbf{e}_i = \left\{\varepsilon_i\ \gamma_{yi}\ \gamma_{zi}\right\}^{\mathbf{T}}\right) \tag{2.7}$$

Where $\mathbf{e}_i$ is the strain vector of the ith fiber, including the normal strain ε_i and the shear strain γ_{yi}, γ_{zi}, n is the number of the fibers.

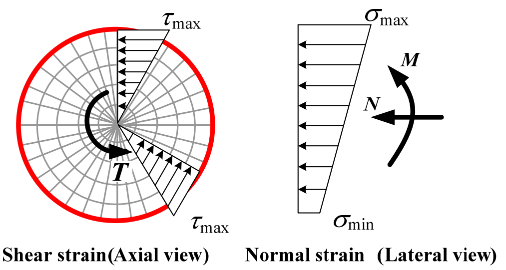

Figure 2.1 Assumption for normal strain and shear strain distribution

The plane section assumption for the normal strain and the linear distribution assumption for the shear strain produced by the torsion moment of circular concrete filled steel tube are used as shown in Figure 2.1. Therefore, the strain vector $\mathbf{e}_i$ of each fiber can be obtained as:

$$\mathbf{e}_i = \mathbf{u}_i \bullet \mathbf{d} \tag{2.8}$$

Where $\mathbf{u}_i$ is the position function of the ith fiber, which can be expressed as:

$$\mathbf{u}_{\mathrm{i}} = \begin{bmatrix} 1 & 0 & 0 & 0 & z_{\mathrm{i}} & -y_{\mathrm{i}} \\ 0 & 0 & 0 & z_{\mathrm{i}} & 0 & 0 \\ 0 & 0 & 0 & y_{\mathrm{i}} & 0 & 0 \end{bmatrix} \tag{2.9}$$

Where y_i and z_i are the coordinate of the ith fiber in the local element coordinate system.

Composing the position function of all the fibers, the matrix **U** is obtained as:

$$\mathbf{U} = \left[\mathbf{u}_1^{\mathbf{T}} \quad \cdots \quad \mathbf{u}_{\mathrm{i}}^{\mathbf{T}} \quad \cdots \quad \mathbf{u}_{\mathbf{n}}^{\mathbf{T}} \right]^{\mathrm{T}} (1 \le \mathbf{i} \le \mathbf{n}) \tag{2.10}$$

Therefore, the relation between the strain matrix **E** of all the fibers on the section and the section generalized strain vector **d** can be established as:

$$\mathbf{E} = \mathbf{U} \bullet \mathbf{d} \tag{2.11}$$

2.5. Transformation from strain of fibers to stress of fibers

The stress matrix **S** of fibers and the tangential stiffness matrix **T** of fibers are defined as:

$$\mathbf{S} = \left[\mathbf{s}_1^{\mathbf{T}} \quad \cdots \quad \mathbf{s}_{\mathrm{i}}^{\mathbf{T}} \quad \cdots \quad \mathbf{s}_{\mathbf{n}}^{\mathbf{T}} \right]^{\mathrm{T}} \quad \left(1 \le \mathbf{i} \le \mathbf{n},\, \mathbf{s}_{\mathrm{i}} = \left\{ \sigma_{\mathbf{i}} \;\; \tau_{\mathbf{yi}} \;\; \tau_{\mathbf{zi}} \right\}^{\mathrm{T}} \right) \tag{2.12}$$

$$\mathbf{T} = \left[\mathbf{t}_1^{\mathbf{T}} \quad \cdots \quad \mathbf{t}_{\mathrm{i}}^{\mathbf{T}} \quad \cdots \quad \mathbf{t}_{\mathbf{n}}^{\mathbf{T}} \right]^{\mathrm{T}} \quad \left(1 \le \mathbf{i} \le \mathbf{n},\, \mathbf{t}_{\mathbf{i}} = \left\{ E_{\mathbf{i}} \;\; G_{\mathbf{yi}} \;\; G_{\mathbf{zi}} \right\}^{\mathrm{T}} \right) \tag{2.13}$$

Where, $\mathbf{s}_i$ is the stress vector of the ith fiber, including the normal stress σ_i and the shear stress τ_{yi}, τ_{zi}. $\mathbf{t}_i$ is the tangential stiffness vector of the ith fiber, including the normal tangential stiffness E_i and the shear tangential stiffness G_{yi} and G_{zi}. n is the number of fibers.

The procedures using the material constitutive model to obtain the stress matrix **S** of fibers and the tangential stiffness matrix **T** of fibers will be given in Part 3 of this paper in detail.

2.6. Transformation from stress of fibers to section generalize stress

The section generalized stress vector $\mathbf{D}(x) = \{\boldsymbol{N}, \boldsymbol{V}_y, \boldsymbol{V}_z, \boldsymbol{T}, \boldsymbol{M}_y, \boldsymbol{M}_z\}^{\mathrm{T}}$ can be directly obtained from the stress matrix **S** of fibers by integrating the stress of all the fibers. Since the nonlinear shear behavior of concrete filled steel tubes cannot be considered in the element proposed by this paper, the linear relations are used for the shear behavior of the section. The integration equations of the section are given below:

$$N = \int_A \sigma_{\mathrm{i}} A_{\mathrm{i}} \mathrm{d}A \,, \quad V_{\mathrm{y}} = S_{\mathrm{y}} \gamma_{\mathrm{y}} \,, \quad V_{\mathrm{z}} = S_{\mathrm{z}} \gamma_{\mathrm{z}} \tag{2.14}$$

$$T = \int_A \tau_{\mathrm{i}} \sqrt{x_{\mathrm{i}}^2 + y_{\mathrm{i}}^2} A_{\mathrm{i}} \mathrm{d}A$$
$$M_{\mathrm{y}} = \int_A \sigma_{\mathrm{i}} z_{\mathrm{i}} A_{\mathrm{i}} \mathrm{d}A \,, \quad M_{\mathrm{z}} = \int_A \sigma_{\mathrm{i}} y_{\mathrm{i}} A_{\mathrm{i}} \mathrm{d}A \tag{2.15}$$

Where A is the area of the section, S_y and S_z are the elastic shear stiffness of the section which can be calculated by the methods proposed by James and Barry (2008).

According to the principle of virtual work, the virtual work $\delta\mathbf{W}_1$ done by the section generalized stress **D** on the section generalized virtual strain δ**d** is equal to the virtual work $\delta\mathbf{W}_2$ done by the stress of all the fibers of the section on the corresponding virtual strain：

$$\begin{aligned} &\boldsymbol{\delta}\mathbf{W}_1 = \mathbf{D}^{\mathrm{T}} \bullet \boldsymbol{\delta}\mathbf{d} \\ &\boldsymbol{\delta}\mathbf{W}_2 = (\mathbf{A} \bullet \mathbf{S})^{\mathrm{T}} \boldsymbol{\delta}\mathbf{E} = (\mathbf{A} \bullet \mathbf{T} \bullet \mathbf{U} \bullet \mathbf{d})^{\mathrm{T}} \mathbf{U} \boldsymbol{\delta}\mathbf{d} \end{aligned} \tag{2.16}$$

$$\boldsymbol{\delta}\mathbf{W}_1 = \boldsymbol{\delta}\mathbf{W}_2$$

Where **S = T·E = T·(U·d)**, The matrix **A** is a diagonal matrix composed by the area of each fiber of the section:

$$\mathbf{A} = \mathbf{diag}(A_1, ...A_k, ..., A_n) \tag{2.17}$$

Introducing Eqn. 2.11 into Eqn. 2.16, the stiffness matrix $\mathbf{k}(x)$ of the section at the integration point in the local element coordinate system can be obtained as:

$$\mathbf{k}(x) = \mathbf{U}^{\mathrm{T}}\mathbf{A}\mathbf{T}_i\mathbf{U} \tag{2.18}$$

2.7. Transformation from section generalize stress to element nodal force

Introducing Eqn. 2.4, the element force vector in the local element coordinate system can be calculated by integrating the section generalized stress of all the integration points of the element:

$$\overline{\mathbf{Q}}_e = \int_0^l \mathbf{N}'(x)^{\mathrm{T}} \mathbf{D}(x)\, \mathrm{d}x \tag{2.19}$$

According to the principle of virtual work, the virtual work $\delta\mathbf{W}_1$ done by the element force on the element virtual displacement is equal to the virtual work $\delta\mathbf{W}_2$ done by the section generalized stress $\mathbf{D}(x)$ of all the integration points on the corresponding section generalized virtual strain $\delta\mathbf{d}(x)$:

$$\begin{aligned} &\boldsymbol{\delta}\mathbf{W}_1 = \overline{\mathbf{Q}}_e^{\mathrm{T}} \boldsymbol{\delta}\overline{\mathbf{q}}_e \\ &\boldsymbol{\delta}\mathbf{W}_2 = \int_0^L [\mathbf{k}(x)\mathbf{d}(x)]^{\mathrm{T}} \boldsymbol{\delta}\mathbf{d}(x)\mathrm{d}x \\ &\boldsymbol{\delta}\mathbf{W}_1 = \boldsymbol{\delta}\mathbf{W}_2 \end{aligned} \tag{2.20}$$

Introducing Eqn. 2.11 into Eqn. 2.20, the element stiffness matrix in the local element coordinate system can be obtained as:

$$\overline{\mathbf{K}}_e = \int_0^L \mathbf{N}'(x)^{\mathrm{T}} \mathbf{k}(x)\mathbf{N}'(x)\ \mathbf{d}x \tag{2.21}$$

2.8. Transformation from local element coordinate system to global coordinate system

Since the element force vector and the element stiffness matrix in the local element coordinate system cannot be used in the finite element analysis for the global structure, the transformation to the global coordinate system is needed. Introducing the geometrical transformation matrix in Eqn. 2.1, the element force vector $\mathbf{Q}_e$ and the element stiffness matrix $\mathbf{K}_e$ in the global coordinate system is obtained as:

$$\mathbf{Q}_e = \mathbf{V}^{\mathrm{T}}\overline{\mathbf{Q}}_e \tag{2.22}$$

$$\mathbf{K}_e = \mathbf{V}^{\mathrm{T}}\overline{\mathbf{K}}_e\mathbf{V} \tag{2.23}$$

3. MATERIAL EQUATIONS

In this part, the procedures for obtaining the stress vector $\mathbf{s}_i$ and the tangential stiffness vector $\mathbf{t}_i$ of concrete and steel fibers based on material constitutive models are illustrated in detail.

The strain state of each fiber is normal-shear state, so the uniaxial material stress-strain relationship is no longer suitable for the material model of fibers. Firstly, the two shear strain γ_{yi} and γ_{zi} produced by torsion in the two mutual perpendicular direction in the local element coordinate system need to be vector superimposed, so the total shear strain γ_i of the ith fiber can be calculated as:

$$\gamma_{\mathrm{i}} = \sqrt{\gamma_{\mathrm{yi}}^2 + \gamma_{\mathrm{zi}}^2} \tag{2.24}$$

Combined with the normal strain ε_i of the ith fiber, the general strain space of the ith fiber is obtained. In order to transform the general strain space to the general stress space, strain compatibility equations, stress equilibrium equations and material constitutive equations must be used, which will be introduced in detail as following.

3.1. Concrete

Because the constitutive law is relatively complicated for the concrete fiber at normal-shear strain state, the general coordinate system of the concrete fiber should be changed into the principal strain coordinate system. Then the concrete constitutive model considering the compression softening effect in the principal strain space can be used. According to the strain compatibility condition, the principal strain vector $\mathbf{e}_{pi}$ of the ith concrete fiber can be calculated as:

$$\mathbf{e}_{\mathrm{pi}} = \begin{Bmatrix} \varepsilon_{\mathrm{pti}} \\ \varepsilon_{\mathrm{pci}} \end{Bmatrix} \begin{bmatrix} 0.5 & \cos^{-1} 2\alpha_{\mathrm{i}} \\ 0.5 & -\cos^{-1} 2\alpha_{\mathrm{i}} \end{bmatrix} \begin{Bmatrix} \varepsilon_{\mathrm{i}} \\ \gamma_{\mathrm{i}} \end{Bmatrix} \tag{2.25}$$

Where ε_{pti} and ε_{pci} are the principal tension strain and principal compression strain of the ith fiber respectively. α_i is the inclination of the principal strain space which can be calculated as:

$$\alpha = 0.5 \arctan(\varepsilon_{\mathrm{i}} / 2\gamma_{\mathrm{i}}) \tag{2.26}$$

In the principal strain space, introducing the concrete constitutive equations, the principal stress vector $\mathbf{s}_{pi}$ of the ith fiber can be obtained as:

$$\mathbf{s}_{\mathrm{pi}} = \begin{Bmatrix} \sigma_{\mathrm{pti}} \\ \sigma_{\mathrm{pci}} \end{Bmatrix} \tag{2.27}$$

Where σ_{pti} and σ_{pci} are the principal tension stress and principal compression stress of the ith fiber respectively, which can be calculated based on the concrete constitutive equations:

$$\sigma_{\mathrm{pti}} = F\left(\varepsilon_{\mathrm{t0}}, \varepsilon_{\mathrm{pti}}\right) \tag{2.28}$$

$$\sigma_{\mathrm{pci}} = \zeta F\left(\zeta \varepsilon_{\mathrm{c0}}, \varepsilon_{\mathrm{pci}}\right) \tag{2.29}$$

Where $\boldsymbol{F}$ is the functions for calculating the stress-strain relationships of the concrete considering confined effect, ε_{t0} and ε_{c0} are the tension peak strain and the compression peak strain of the confined concrete, ζ is the compression softening coefficient used to consider the influence of the concrete cracks in the principal tension direction on the behavior of the concrete in the principal compression direction.

3.1.1 Uniaxial stress-strain relations of confined concrete

The compression stress-strain relationships of confined concrete proposed by Han (2007) are used. The skeleton curves for circular concrete filled steel tube are:

$$F = 2x - x^2 \qquad (x \le 1)$$

$$F = \begin{cases} 1 + q(x^{0.1\xi} - 1) & (\xi \ge 1.2) \\ \dfrac{x}{\beta(x-1)^2 + x} & (\xi < 1.2) \end{cases} \qquad (x > 1) \tag{2.30}$$

Where $x=\varepsilon/\varepsilon_0$, $F=\sigma/\sigma_0$, $\sigma_0=[1+(-0.054\xi^2+0.4\xi)(24/f_c')^{0.45}]\,f_c'$, $\varepsilon_0=\varepsilon_{cc}+[1400+800(f_c'/24-1)]\xi^{0.2}(\mu\varepsilon)$, $\varepsilon_{cc}=1300+12.5\,f_c'\,(\mu\varepsilon)$, $q=\xi^{0.745}/(2+\xi)$, $\beta=(2.36\times10^{-5})^{[0.25+(x-0.5)7]}\,f_c'^2\times3.51\times10^{-4}$。 f_c' is the compressive strength of standard cylinder concrete.

The tension stress-strain relationships of confined concrete is assumed to be as the same as that of the common concrete. The tension stress-strain relation before the strain reaches the tension peak strain is linear elastic, and the elastic tension modulus is equal to the elastic compression modulus. The smeared crack model is used for describing the post cracking behavior of concrete, and the linear relationship is used for descending stage of the stress-strain curve of the post-cracking concrete..

3.1.2 Softening coefficient

In the principal stress space of the concrete fiber, the peak strain and stress were both lower than those at uniaxial compression stress state, which was defined as “compression softening effect”. The compression softening coefficient for reducing the peak stress and strain in the principal compression direction was proposed in order to consider the compression softening effect due to cracking in the principal tension direction. The method for calculating the compression softening coefficient ζ proposed by (Belarbi and Hsu, 1995) is used in this paper:

$$\zeta = 1.0 / \sqrt{1 + 400\varepsilon_{pt}} \tag{2.31}$$

Where ε_{pt} is the principal tension strain.

After the principal stress space of the concrete fiber is obtained, the general stress space of the ith concrete fiber can be calculated based on the stress equilibrium conditions, so the stress vector of the ith concrete fiber in the general stress space is:

$$\begin{Bmatrix} \sigma_i \\ \tau_i \end{Bmatrix} = \begin{bmatrix} 0.5 & \cos^{-1} 2\alpha_i \\ 0.5 & -\cos^{-1} 2\alpha_i \end{bmatrix} \begin{Bmatrix} \sigma_{pti} \\ \sigma_{pci} \end{Bmatrix} \tag{2.32}$$

3.2 Steel

The perfect elastic-plastic model is chosen for the steel material. In the elastic stage, the stress-strain relationship can be determined as:

$$\boldsymbol{\sigma} = \mathbf{D}_e \bullet \boldsymbol{\varepsilon} \tag{2.33}$$

Where $\boldsymbol{\sigma}=\{\sigma_s, \tau_s\}^T$ is the stress vector of the steel fiber, $\boldsymbol{\varepsilon}=\{\varepsilon_s, \gamma_s\}^T$ is the strain vector, and $\mathbf{D}_e$ is the elastic Jacobian matrix given below directly：

$$\mathbf{D}_e = \begin{bmatrix} E_s & 0 \\ 0 & G_s \end{bmatrix} \tag{2.34}$$

Where E_s and G_s are the Young modulus and elastic shear modulus of the steel material.

The Classic Von-Mises yield criterion and the associated flow rule are chosen for the steel material (Chen, 2004). Through several steps of derivations and transformations based on principles in elasticity and plasticity mechanics, the relationship between the incremental stress vector $d\boldsymbol{\sigma}$ and the incremental strain vector $d\boldsymbol{\varepsilon}$ in the elastic-plastic stage can be obtained as:

$$\mathbf{d\sigma} = \mathbf{D}_{ep} \bullet \mathbf{d\varepsilon} \tag{2.35}$$

Where $\mathbf{D}_{ep}$ is the Jacobian matrix of the steel material at elastic-plastic stage:

$$\mathbf{D}_{ep} = \frac{E_s G_s}{E_s \sigma_s^2 + 9G_s \tau_s^2} \begin{bmatrix} 9\tau_s^2 & -3\sigma_s \tau_s \\ -3\sigma_s \tau_s & \sigma_s^2 \end{bmatrix} \tag{2.36}$$

In this section, the stress-strain relationship of steel fibers is obtained, so the general strain space of steel fibers can be transformed into the general stress space.

Through the procedures in part 3.1 and part 3.2, the general stress space of concrete and steel fibers are obtained from the general strain space. Then the stress vector $\mathbf{s}_i=\{\sigma_i, \tau_{yi}, \tau_{zi}\}^T$ of the ith fiber in the local element coordinate system can be composed, and the tangential stiffness vector $t_i=\{E_i, G_{yi}, G_{zi}\}^T$ of the ith fiber can be also calculated based on the incremental stress-strain relationship of fibers.

4 SOLUTION AND VERIFICATIONS

Based on the procedures shown in part 3 and the Newton-Raphson iterative solution method, a nonlinear analysis program is developed using FORTRAN language in order to use the fiber beam-column element considering torsion. Therefore, the combined compression-bending-torsion effect can be considered in the concrete filled steel tube columns.

The predicted results and test results of concrete filled steel tube columns subjected to combined compression-bending-torsion load are shown in Figure 3.1. From the comparison it can be seen that the proposed fiber beam-column element considering torsion effect has high accuracy in predicting the torsion behavior of concrete filled steel tube columns subjected to combined compression bending and torsion load. Furthermore, compared with the traditional three-dimensional refined finite element model, the high modeling speed and solution speed can be achieved using the fiber beam-column model considering torsion effect proposed by this paper.

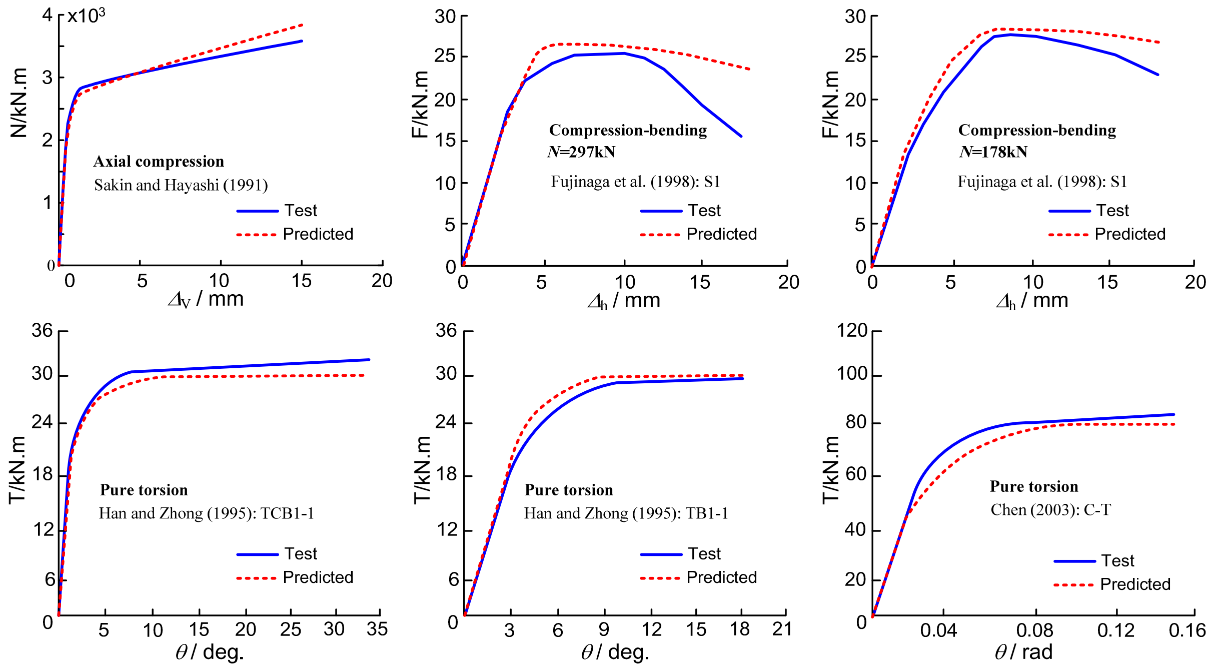

Figure 3.1 Comparison between predicted results and test results

5 CONCLUSIONS

A new fiber beam-column element considering torsion effect for analyzing the nonlinear behavior of concrete filled steel tube columns subjected compression-bending-torsion combined action was proposed, and a nonlinear solution program using the Newton-Raphson method for obtaining the entire loading history was also developed. The proposed fiber beam-column model considering torsion effect had high modeling speed and solution speed, so the torsion behavior of concrete filled steel tube columns can be analyzed in detail.

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