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Mechanical Model of Initial Stiffness of Outer Shell Joints based on Component Method

Dan Zhang¹, Lei Zhang²

Lecturer, College of Civil Engineering, Hunan City University, Yiyang, China¹

Engineer, College of Civil Engineering, Hunan City University, Yiyang, China²

ABSTRACT: Square steel tube column-H-shaped steel beam new outer shell joint refers to the installation of reinforced steel plates outside the wall of the square steel tube column in the core area of the joint to enhance the rigidity of the beam-column joint. The initial rotational stiffness of a joint is an important indicator that reflects the deformation capacity of the joint at the initial stage of loading. However, the method of determining the initial stiffness of the joint by experiment or numerical simulation will generate a lot of time and labor costs. In order to put forward a simple and accurate analysis method, this study established the initial stiffness mechanical model of the outer shell joint based on the component method in the Eurocode3 specification, clarified the force mechanism of the joint, and avoided a large number of experimental research and finite element simulation. In this method, the beam-column node was equivalent to a combination of multiple components, and the initial stiffness mechanical model of each component and node in the elastic phase was established. On this basis, the initial rotational stiffness of the node was calculated and compared with the test results. The mechanical model of the outer shell joints based on the component method provides references for the design and application of steel structures.

KEYWORDS: Outer shell joint, Component method, Mechanical model, Initial stiffness.

I. INTRODUCTION

The mechanical properties of beam-column joints have a significant impact on the overall bearing capacity, stiffness, stability and seismic performance of the steel structure. The joint is a complex part of the steel structure system. The initial rotation stiffness of the joint is an important indicator that reflects the deformation ability of the joint at the initial stage of loading. At present, the initial rotational stiffness of a joint is determined by experiment or numerical simulation. However, with the continuous improvement of the joint structure, it is difficult to ensure sufficient test data for different forms of joints. Therefore, the establishment of a theoretical model can efficiently solve the problem of diversified joint parameters.

The Eurocode3 specification (EC3) recommends the component method for joint design. The component method is to split the node into multiple components, each component is simulated by springs, and then the springs are combined in series and parallel to obtain the overall mechanical properties of the node. Compared with the test method and numerical analysis, the component method has a clear mechanical model, which is convenient to understand the internal working mechanism of the node, and the failure sequence of different components can be determined through theoretical calculation. However, for square steel tube column-H-shaped steel beam outer shell joints, there are few studies on the initial stiffness mechanics model, therefore, it is necessary to further study the application of the component method in the outer shell joints.

Paper is organized as follows. Section II describes the basic principle of component method and its application in steel joints. In Section III, the initial stiffness mechanical model of each component and the outer shell joint is given. In Section IV, the comparison between the initial stiffness calculation results and the test results based on the component method is given. Finally, Section V presents conclusion.

II. RELATED WORK

In EC3 [1], it is proposed to divide the load-bearing performance of the joint into a series of independent basic components, and the mechanical properties of the activated components were represented by springs with the same or similar mechanical properties, that was, the so-called component method. In [2], theoretical analysis on the initial rotational stiffness of the connection in assembled-type light-steel (ATLS) modular house was discussed based on the component method. However, the theoretical results lack further verification by joint experiments. Gil-Martín et

al.[3] presented a new approach of the component method for steel connections. All the information regarding the behavior of the joint was obtained by using basic kinematic conditions and solving a simple system of equations. However, only translational springs connected in series are considered.

Pouring concrete in the steel tube column can effectively improve the mechanical properties of the joints. Fan et al. [4] proposed an analysis model of initial rotational stiffness for concrete filled steel tube (CFST) column joints according to component method. The initial rotational stiffness can be calculated straight by material properties and measurement factors. Similarly, Zhao et al. [5] established the calculation model of the initial rotational stiffness of the CFST column-steel beam extended end-plate connection based on the component method, taking into account the influence of end-plate bending, end-plate shearing, bolt tension, steel tubular web shearing and column core concrete shear deformation on the rotational stiffness of the joints. However, the deformation of the CFST joints is only considered in tension zone, the deformation of compression zone is ignored. Gao et al. [6] analyzed and established the mechanical models of the CFST column joints connected by different types of piercing bolts based on the component method, and proposed the calculation formula of the stiffness coefficient of the piercing bolt connection, which was not involved in EC3. Yet the structural force transmission of the piercing bolt connection is relatively complex. When the beam-column joint adopts circular tubular column, Wang et al. [7] numerically assessed the initial stiffness of stainless steel composite bolted joints with concrete-filled circular tubular (CFCT) columns. A modified component method was proposed to better predict the flexural behaviour of joints containing circular columns and curved endplates. Obviously, the mechanical model of circular column is more complex than that of rectangular column. The calculation models of initial rotational stiffness of joints in the above literature are applicable to specific node types. Therefore, it is necessary to establish a mechanical model suitable for outer shell joints.

The work in this study is divided in two stages. 1) Establish the mechanical model of initial stiffness and 2) verify the mechanical model. The initial stiffness mechanical model determines the stiffness of the activated component through the mechanical theory, and uses the corresponding spring to simulate. Thereafter, the springs are combined to obtain the simplified mechanical model of the joint. Finally, the stiffness of each component is calculated, and the initial stiffness of the node domain is obtained through the combined spring system, which is compared with the experimental results to verify its accuracy.

III. METHODOLOGY

This study took the outer shell joints of square steel tubular column-H-shaped steel beam [8] as the analysis objects, as shown in Figure 1. The component method recommended in EC3 was used to calculate the initial stiffness of steel joints. Firstly, different components included in the connection were determined, then the components were simplified into springs with certain stiffness coefficient according to the principle of component method of calculating the joint stiffness, and the components were reassembled according to their position to form a component model composed of springs and rigid rods. For the outer shell joints, the rotation deformation mainly comes from three aspects, i.e. the tension of T-stub parts, the tension and compression of column flange and the shear deformation of column web. The calculation method of the initial stiffness of each component is introduced below.

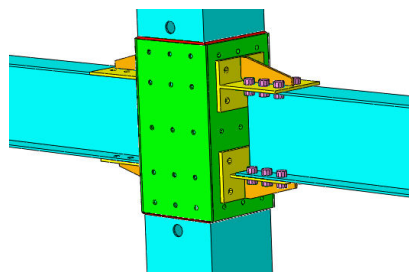


Fig. 1. Schematic diagram of outershell joints of square steel tube column-H-shaped beam

Tensile stiffness of T-stub parts

Under the action of axial tension, the T-stub parts may produce three failure modes, namely, bolts failure, plastic hinge failure of T-stub flange and combined failure modes, as shown in Figure 2. Therefore, it can be judged that the activated components include tensile high-strength bolts, T-stubflange under moment and shear, and tensile T-stubweb

[9]. The initial stiffness of these three components can be calculated respectively, the mechanical properties of T-stub parts can be obtained after combination.

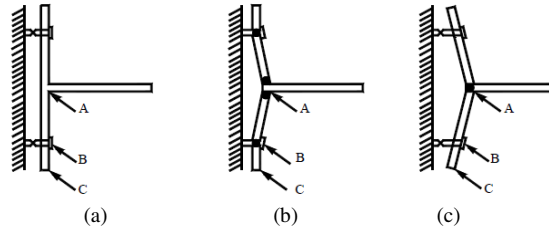


Fig. 2. Failure modes of T-stub parts (a) Bolts failure (b) Plastic hinge failure of T-stub flange (c) Combined failure

(1) Tensile stiffness of high strength bolt k_{bt}

Ignoring the influence of shear force on high-strength bolt, the tensile deformation value Δ_{bt} of high-strength bolt in elastic stage is

$$\Delta_{bt} = \frac{F_t l_{bt}}{mEA_b} \tag{1}$$

Initial stiffness of bolt in elastic stage k_{bt} is:

$$K_{bt} = \frac{F_t}{\Delta_{bt}} = \frac{mEA_b}{l_{bt}} \tag{2}$$

Where F_t is the axial tension on the beam flange converted by the bending moment at the beam end, l_{bt} is the length of the bolt rod (i.e. the sum of the flange thickness of the T-stub and the flange thickness of the column in the node area), m is the number of high-strength bolts on one side of the tensile area, E is the elastic modulus of bolt material, A_b is the cross-sectional area of the bolt.

(2) Stiffness of T-stub flange k_{fv}

The stiffness of T-stub flange is defined as the ratio of the horizontal tension to the deformation. According to the material mechanics, the deformation of flange plate under tension Δ_{fv} is:

$$\Delta_{fv} = \sum \int \frac{\bar{M}M_p}{EI} ds + \sum \int \frac{\bar{F}_N F_{NP}}{EA} ds + \sum \int \frac{k\bar{F}_Q F_{QP}}{GA} ds \tag{3}$$

The stiffness of the flange plate is composed of section AB and section BC in Figure 2, expressed as k_{fv1} and k_{fv2} respectively. Where M_p, F_{NP} and F_{QP} are the bending moment, the axial force and the shear force generated by the actual force of the T-stub flange respectively. \bar{M}, \bar{F}_N and \bar{F}_Q are the internal forces generated by the T-stub flange under the action of unit load. I is the moment of inertia of flange section, G is the shear modulus of steel, k is the section deformation coefficient of shear strain, and the value of rectangular section is $6/5$.

The axial force of AB section of T-stub flange is ignored, the displacement generated under bending moment and shear force Δ_{fv1} is:

$$\Delta_{fv1} = \sum \int \frac{\bar{M}M_p}{EI} ds + \sum \int \frac{k\bar{F}_Q F_{QP}}{GA} ds = V \left(\frac{5l_{ab}^3}{48EI} + \frac{kl_{ab}}{GA_{fv}} \right) \tag{4}$$

Where V is the shear force on the flange section, l_{ab} is the length of section AB, A_{fv} is the cross-sectional area of the T-stub flange.

Then the stiffness of section AB is

$$K_{fv1} = \frac{V}{\Delta_{fv1}} = \frac{1}{\frac{5l_{ab}^3}{48EI} + \frac{kl_{ab}}{GA_{fv}}} \tag{5}$$

Poisson's ratio is taken as 0.3, then

$$K_{fv1} = \frac{EA_{fv}t_f^2}{l_{ab}(1.25l_{ab}^2 + 3.12t_f^2)} \tag{6}$$

Where t_f is the thickness of the T-stub flange.

Ignoring the action of axial force and bending moment, displacement of BC section Δ_{fv2} under shear force V is:

$$\Delta_{fv2} = \sum \int \frac{k\bar{F}_Q F_{QP}}{GA} ds = \frac{kV l_{bc}}{GA_{fv}} \tag{7}$$

Then the stiffness of section BC is

$$K_{fv21} = \frac{V}{\Delta_{fv2}} = 0.32 \frac{EA_{fv}}{l_{bc}} \tag{8}$$

Where l_{bc} is the length of section BC.

(3) Stiffness of T-stub web k_{wt}

According to the material mechanics, when the web is in the elastic stage, its tensile stiffness is:

$$K_{wt} = \frac{EA_w}{h_w} \tag{9}$$

Where h_w is the height of tensile web, A_w is the cross-sectional area of the T-stub web.

Since there is partial compressive stress at the end of the T-stub flange when the joint stress is small, the flange plate can be regarded as a lever, and the stress at the bolt is the sum of the end pressure and the web tension. The T-stub model composed of springs and rods can be combined according to the position and relationship of each component, as shown in Figure 3.

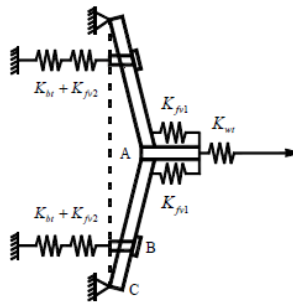


Fig. 3. Component model of the T-stub

Then the initial tensile stiffness of the T-stub K_T is:

$$K_T = \frac{1}{\frac{1}{2\left(\frac{1}{K_{fv2}} + \frac{1}{K_{bt}}\right)} \times \frac{l_{bc}}{l_{ac}} + \frac{1}{2K_{fv1}} + \frac{1}{K_{wt}}} \tag{10}$$

Where l_{ac} is the length of section AC.

Tensile stiffness of square steel tubular column flange

The column flange in the tension zone is simplified as a two-way plate subjected to the concentrated tension of four bolts. Assuming that the outer shell and the column flange work together, the two jointly resist the horizontal tension from the high-strength bolts. The yielding mechanism of the column flange is shown in the Figure 4(a). The concentrated force is further converted into uniform load on the surface, then the column wall can be regarded as a four-sided simply supported two-way slab, as shown in Figure 4(b).

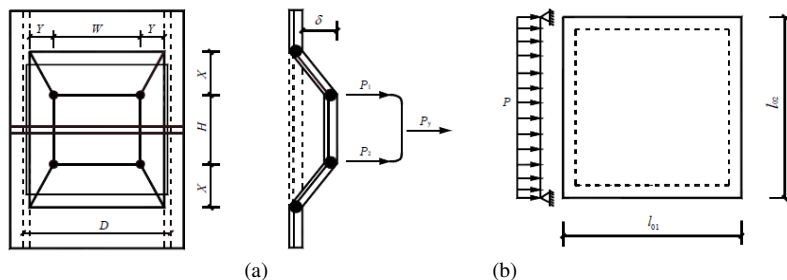


Fig. 4. Stress model of square steel tube column flange (a) Yield mechanism of column flange (b) Four-sided simply supported two-way slab

The flexural stiffness of the column flange simplified as a two-way slab is

$$B_c = \frac{Et_c^3}{12(1 - \nu^2)} \tag{11}$$

In the formula, t_c is the thickness of the column wall (the sum thickness of the column flange and the outer shell), and ν is the Poisson ratio. The deformation of the column flange under uniform load Δ_{cf} is

$$\Delta_{cf} = \frac{2fp l_{01}^4}{B_c} = \frac{24fF_t l_{01}^3(1 - \nu^2)}{l_{02}Et_c^3} \tag{12}$$

Then the tensile stiffness of the column flange K_c is

$$K_c = \frac{F_t}{\Delta_{cf}} = \frac{l_{02}Et_c^3}{24fl_{01}^3(1 - \nu^2)} \tag{13}$$

Where p is the uniformly distributed load acting on the two-way slab, l_{01} and l_{02} are the short and long sides of the two-way slab, respectively, f is the the column wall deformation coefficient related to the ratio of l_{01}/l_{02} .

The compression of the outer shell joint is mainly due to the compression of the column wall, that is, the column flange in the reinforcement area of the outer shell is compressed. If it is simplified as a compressed two-way plate, the initial compressive stiffness K_{cwc} equals the tensile stiffness of the column flange K_c .

Shear stiffness of square steel tube column web

It is approximately considered that the column web is in a state of pure shear stress, as shown in Figure 5.

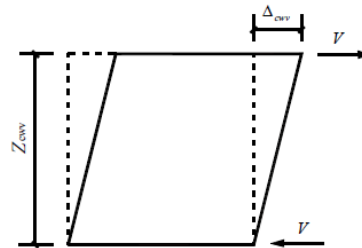


Fig. 5. Shear deformation of column web

The shear deformation of the column web under the action of the shear force V is

$$\Delta_{cwv} = \frac{VZ_{cwv}}{GA_{cwv}} = \frac{F_t(h_b + t_w)}{GA_{cwv}} \tag{14}$$

In the formula, Z_{cwv} is the height of the shear area of the column web. For the outer shell joint, $Z_{cwv} = h_b + t_w$, where h_b is the section height of the H-shaped steel beam, t_w is the thickness of the T-stub web, and A_{cwv} is the shear cross-sectional area of the column web (the sum of the cross-sectional areas of the column web and the outer shell).

Poisson's ratio is taken as 0.3, the shear stiffness of the column web K_{cwc} is obtained as

$$K_{cwc} = \frac{GA_{cwv}}{Z_{cwv}} = \frac{EA_{cwv}}{2.6(h_b + t_w)} \tag{15}$$

Component-based mechanical model of outer shell joints

According to the geometric and mechanical parameters of each component, the tensile stiffnesses, compressive stiffnesses, and shear stiffnesses of the core area of the node are calculated, and each component is simulated by springs with the same stiffness, then the overall node can be simplified as a component model consisting of a series of springs and rods, as shown in Figure 6.

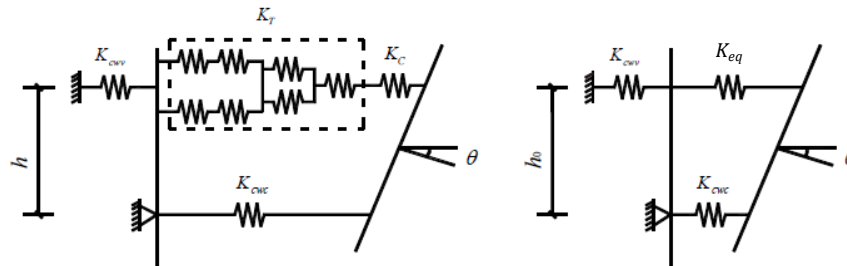


Fig. 6. Mechanical model of the outer shell joint based on component method (a) Spring model (b) Simplified model

When the lower flange of the steel beam is used as the rotation center, the stiffness of tension zone can be simplified as an equivalent tensile stiffness K_{eq} , and the corresponding equivalent height is h_0 . According to the series-parallel combination of springs, the equivalent tensile stiffness K_{eq} can be expressed as:

$$K_{eq} = \frac{1}{\frac{1}{K_T} + \frac{1}{K_C}} \quad (16)$$

Under the action of the bending moment M , the rotation angle θ of the nodal domain is calculated as follows:

$$\theta = \frac{M}{h_0^2} \left(\frac{1}{\frac{1}{K_{eq}} + \frac{1}{K_{cwc}} + \frac{1}{K_{cwv}}} \right) \quad (17)$$

The initial rotational stiffness of the node K'_0 can be obtained

$$K'_0 = \frac{M}{\theta} = \frac{h_0^2}{\frac{1}{K_{eq}} + \frac{1}{K_{cwc}} + \frac{1}{K_{cwv}}} \quad (18)$$

IV. CALCULATION RESULTS

In order to verify the rationality of the mechanical model of the initial stiffness of the outer shell joint based on the component method, taking the test specimens STj-A and STj-B [8] as examples. The proposed component mechanical model is used to calculate the initial rotational stiffness of the joint, and compared with the test results. The calculation results are shown in Table 1.

Table 1. Comparative analysis of theoretical and experimental values of initial stiffness of outer shell joints

Specimen	Experimental value K_0 ($kN \cdot m \cdot rad^{-1}$)	Theoretical value K'_0 ($kN \cdot m \cdot rad^{-1}$)	$(K_0 - K'_0) / K'_0$
STj-A	5025.27	4936.4	1.8%
STj-B	12635.40	12267.5	3%

From the comparative analysis in Table 1, it can be seen that the theoretical values of the initial rotational stiffness of the outer shell joints are in good agreement with the experimental values, and the difference is within 5%. The accuracy can meet the requirements of engineering design, indicating that the selection of joint connection components is reasonable, the given formula can accurately calculate the initial rotational stiffness of the connection. The mechanical model of the initial stiffness of the outer shell joint based on the component method is simple and effective, which provides a theoretical basis for the design of the outer shell joints.

V. CONCLUSION

On the basis of the component method, the component mechanical model of the outer shell joint and the calculation method of the initial stiffness were deduced. The tensile stiffness of the T-stub, the tensile and compressive stiffness of the square steel tube column flange and the shear stiffness of the square steel tube column web were deduced respectively. The components of the nodal domain were converted into a simplified mechanical model composed of a series of springs and rods. The calculation method of the initial rotational stiffness of the joints was derived using the component method. The deduced calculation method of the initial rotational stiffness of the outer shell joints is in good agreement with the test results, and the difference is within 5%, the calculation accuracy is high.



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