Bearing Capacity of Steel Tube Tower Connection under Different Thickness of Gusset Plate

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Abstract. In this paper, a finite element model is established to study the influence of connection plate thickness on the bearing capacity of steel tube tower connections. Through the bearing capacity of connections under different connection plate thickness, the influence of connection plate thickness on the bearing capacity of steel pipe tower connections is analyzed. Finally, the relationship between the thickness of connection plates and the bearing capacity of steel tube tower connections is analyzed by regression analysis. The results show that with the increase of the thickness of gusset plate, the bearing capacity of steel tube tower connections increases linearly. The bearing capacity calculated by regression analysis is in good agreement with the finite element simulation results.

1. Introduction
The height of the transmission tower increases with the improvement of the voltage level of the transmission line, the load on the wire and other loads are also increasing, especially in the long-span transmission line. The connection is the key part of the transmission tower structure. So far, some researches on tower connections have been carried out in the domestic and overseas. Whitemore[1] experimentally studied the elastic stress distribution of Warren truss connection plates and put forward the famous effective width theory. Through the experimental study, it is found that the stress of the connection plate is almost not distributed outside the effective width. Chakrabarti[2] and Bjorhovde[3] conducted full-scale experiments on gusset plates with different connection parameters, considering the buckling of the gusset plate caused by the second-order effect of the load, and studied the tensile performance of the gusset plate, as well as the ultimate bearing capacity of the connection and its failure form. Korol[4] through the test of rectangular steel tube plate connections, it is concluded that most of the specimens are due to the failure caused by shear lag. Lutz[5] found that the failure of the gusset plate is mainly the overall buckling of the connection plate. Based on the analysis results, the design method and measures of the gusset plate are proposed.

Yu [6] conducted full-scale experimental research and theoretical analysis on the K-connection of steel tube tower and tube plate, discussed and introduced the analysis model of connection limit bearing. Ju Yanzhong et al. [7-9] established a finite element model for the K-type connection of steel tube angle steel combined tower, the finite element model was established according to contact. And studied the effects of angular steel pipe board connection parameters on ultimate bearing capacity, and put forward...
that there are three main failure modes of steel pipe angle steel composite tower. Chen [10] also analyzes the finite element model of the transmission steel tube tower K-connection, analyzed the thickness of angular steel, the length of the connection plate and the bearing capacity of K-connections. Qu [11-12] studied the bearing capacity and influencing factors of the tube plate is connected to the K-connection, and put forwarded the calculation formula of ultimate strength. Antimo [13] studied the bearing resistance of tubular members, with gusset plates and through-all long bolts. Li [14] studied the ultimate strength of the kt node of the 1/4 ring plate stiffened pipe gusset plate to predict, based the study proposed one design formula for ultimate strength based on yield line theory. Nie [15] proposed the form of steel pipe double-billed connections, and compared and analyzed the mechanical properties of tube-single-limb connection and tube-leg two-billed connection finite element simulation by electrostatic load experiments.

Through the research literature of angle steel tube plate connections, it is found that although there are traces to follow, it is not very in-depth. Therefore, in this paper, the finite element model of steel pipe angle steel composite tower connections is established by using ANSYS finite element software, the ultimate bearing capacity of connections is analyzed, the influence of connection plate thickness on the failure mode and ultimate bearing capacity of angle steel connections is studied, and the regression curve of ultimate bearing capacity of angle steel tube plate connections and nodal plate thickness is established.

2. Establishment of geometric parameters and finite element model of angle steel tube plate connections

2.1 Geometry parameters
This paper studied the effects of connection plate thickness on connection ultimate bearing capacity. The geometric parameters of this kind of connections include steel pipe length $L$, steel pipe diameter $D$, pipe wall thickness $t$, steel pipe diameter-thickness ratio $\gamma = D/t$, connection plate length $L_p$, connection plate width $W_p$, connection plate thickness $t_p$; angle steel length $L_j$, angle steel edge width $W_j$, angle steel thickness $t_j$, angle steel corner $\theta$, angle steel limb end face midpoint along the axis direction to the steel pipe top wall clear distance (referred to as clear distance).

In this paper, the steel pipe having a diameter of 159 mm is selected. The length of the steel pipe is approximately 6 times that of the steel pipe diameter. It is to avoid the influence of the connection area of the steel pipe, and the diameter selected is 950mm. the width of connection plate is 350mm. At the same time, it is assumed that the steel pipe bears the axial force $N = 0$ and the angle steel inclination $\theta = 50^\circ$.

2.2 Unit selection
This paper used ANSYS10.0 software for nonlinear large deformation elastoplastic analysis of K-type connections of angular steel pipe plate. In order to simulate the eccentricity of the angular steel on one side of the node plate, the three-dimensional solid element SOLID92 is used to simulate and use a plane to the planar contact element CONTA174 and the target element rail to mute 170 analog to the interaction between the node plate and the angular steel plate.

2.3 Material performance and meshing
In this paper, the K-connection parameters of steel tube angle steel composite tower are as follows: connection plate and angle steel Q235, elastic modulus $E = 2.06 \times 10^5$ MPa/mm$^2$, Poisson's ratio 0.3. 8.8 grade high strength bolts are adopted and the ideal elastoplastic constitutive relation model is adopted. The two materials conform to Von Mises yield criterion and related flow law, and the model is divided by free mesh. In order to simplify the finite element model, the connections on the interface between the connection plate and the steel pipe are coupled with degrees of freedom to simulate the welding connection of the K-type connections of the Angle steel tube sheet.
2.4 Boundary conditions and load application

According to the actual stress situation of the angle steel tube sheet K-connection in the truss structure of the transmission tower, when establishing the finite element model, the radial direction of the angle steel is constrained, and only the axial displacement of the angle steel is allowed. There are two forms of steel pipe constraints. When the influence of the axial force of the steel pipe on the ultimate bearing capacity of the connection plate is not considered, the constraint form of the steel pipe is fixed at one end and hinged at the other end; when the axial force is considered, the constraint form of the steel pipe is fixed at one end and applied axial force at one end. According to the load, it is found that most of the angle steel of the truss connection is in the pressure state of the lunar axis, and the connection load is uniformly distributed on the angle steel, pulling one angle steel of the two angle steel and compressing the other angle steel.

The loading mode is hierarchical loading, and the loading is stopped when the nodal plate is destroyed. The overall instability load of the nodal plate is calculated by Newton-Raphson iterative method. When the load of the angle steel tube K-connection is close to the ultimate load, the arc length method can be used to calculate the descending section of the load-displacement curve of the connection plate.

3. Failure mode of angle steel tube plate K-connections

Consider connection geometric parameters such as gusset plate thickness, gusset plate length, steel tube thickness, and net supply, cross-setting 81 sets of node models, establish finite element models of each connection to obtain extreme bearing capacity and damage mode of each connection.

When the thickness of the angle bracing plate is 6, 8, 10, 12, 14 and 16mm, the unstable failure of the angle steel pipe plate K-connection occurs. When the thickness of the angle bracing plate is 18mm and the thickness of the steel pipe is 5, 7 and 9mm, the steel tube instability of the K-connection of the angle steel tube sheet will fail, otherwise the instability of the angle bracing plate will fail. When the thickness of the angle bracing plate is 20mm and the thickness of the steel pipe is 5, 7 and 9mm, the steel pipe instability of the angle steel tube plate k-connection will fail, otherwise the failure of the connection plate will occur. When the thickness of the angle bracing plate is 22mm and the thickness of the steel pipe is 5, 7 and 9mm, the steel tube instability of the K-connection of the angle tube plate will fail, otherwise the instability of the angle bracing plate will occur. The steel tube instability mode and the angle support plate instability mode are shown in figure 1.

4. The influence of the thickness of angle steel tube plate K-connections on the bearing capacity

By setting different thickness of the gusset plate, the average value of the ultimate bearing capacity of the angle steel tube plate K-connection is obtained. The relationship between the thickness of the gusset plate($t_p$) and the ultimate bearing capacity of the connection($P$) is shown in Figure 2. It can be found from Figure 4 that as the gusset plate thickness increases, the ultimate bearing capacity of the connection
shows a linear growth trend. This is because as the thickness increases, the lateral stiffness of the gusset plate increases, and the ability of the gusset plate to resist the outer displacement of the plate and the torsion of the angle steel increases.

Figure 2. Trend diagram of ultimate bearing capacity of connections($P$) and thickness of gusset plates($t_p$).

5. The relationship between the bearing capacity of angle steel tube plate K-connection and the thickness of the gusset plate

According to the results of finite element analysis data, the regression analysis was carried out by using ORIGIN software. Through fitting, the regression equation between the ultimate bearing capacity of connections($P$) and the thickness of gusset plate($t_p$) is obtained as follows:

$$P = 48.46 \times (t_p + 1.56) \quad 6\text{mm} \leq t_p \leq 22\text{mm}$$  \hspace{1cm} (1)

The results of the ultimate bearing capacity of connections calculated by finite element method and regression formula respectively are given in Table 1. Based on the results of finite element method, the relative errors between them are compared. As can be seen from Table 1 that the relative error of the ultimate bearing capacity of the connection is about 2%, and the average absolute value of the relative error is about 1%.

Table 1. Comparison of finite element calculation results and formula related to $t_p$ calculation results.

| Gusset plate thickness $t_p$(mm) | Finite element calculation result (kN) | Regression formula calculation result (kN) | Error (%) |
|---------------------------------|----------------------------------------|-------------------------------------------|-----------|
| 6                               | 363.42                                 | 366.358                                   | -0.008    |
| 8                               | 461.10                                 | 463.278                                   | -0.005    |
| 10                              | 552.37                                 | 560.198                                   | -0.014    |
| 12                              | 657.66                                 | 657.118                                   | 0.001     |
| 14                              | 762.18                                 | 754.038                                   | 0.011     |
| 16                              | 873.20                                 | 850.958                                   | 0.025     |
| 18                              | 938.41                                 | 947.878                                   | -0.010    |
| 20                              | 1050.65                                | 1044.798                                  | 0.006     |
| 22                              | 1128.16                                | 1141.718                                  | -0.012    |

Error= (Finite element calculation result- Regression formula calculation result) / Finite element calculation result.
6. Conclusion
In this paper, by establishing the finite element model of angle steel tube plate connections, the influence of gusset plate thickness on the bearing capacity of steel tube tower connections is analyzed, and the relationship between them is analyzed by establishing the regression curve between connection plate thickness and angle steel plate ultimate bearing capacity. The detailed conclusions are as follows:

(1) Considering the material nonlinearity and contact nonlinearity, a finite element model of the angle steel tube plate connection is established. The finite element model of the connection is loaded and it is found that there are gusset plate instability modes and steel tube instability modes under different gusset plate thicknesses.

(2) The finite element analysis results show that the gusset plate thickness has notable effect on the bearing capacity of the angle steel tube plate connection. With the increase of the gusset plate thickness, the bearing capacity of the angle steel tube plate connection shows a linear growth trend.

(3) The relationship between the gusset plate thickness and the bearing capacity of the angle steel tube plate connection is obtained through regression formula: \( P=48.46 \times (t_p+1.56) \). The connection bearing capacity calculated by the formula is not much different from the finite element simulation result.

References
[1] Whitmore R. E. (1952) Experimental investigation of stresses in gusset plate. Engineering Experiment Station, University of Tennessee.
[2] Chakrabarti S. K. (1983) Tests of gusset plate connections. University of Arizona, Tucson.
[3] Bjorhovde R, Chakrabarti S. K. (1985) Tests of full-size gusset plate connections. Journal of Structural Engineering, 111:667-684.
[4] Korol R. M. (1996) Shear lag in slotted HSS tension members. Canadian Journal of Civil Engineering, 23:1350-1354.
[5] Lutz D.G, LaBoube R.A. (2004) Behavior of thin gusset plates in compression. Thin-Walled Structures, 43:861-875.
[6] Yu S.C, Sun B. N, Ye Y, et al. (2004) Experimental study and theoretical analysis of ultimate strength steel tubular joint of tall tower. Engineering mechanic, 21:155-161.
[7] Ju Y. Z, Lei J. F, Zeng J. H, et al. (2011) Analysis on gusset plate failure mode of tube-angle combo tower. East China electric power, 39:1238-1243.
[8] Ju Y. Z, Wang D. H. (2015) Nonlinear Finite Element Analysis of the Ultimate Strength of Tube-Angle Combo Tower K-Joints*. Strength of Materials, 47:355-61.
[9] Ju Y. Z, Li J. Y, Wang D. H, Bai J. F. (2018) Study of the Ultimate Load Capacity of K-Type Tube-Gusset Plate Connections. International Journal of Steel Structures.
[10] Chen J. B, Lei J. F. (2015) Analysis on influence factor on ultimate bearing capacity of K node of power transmission tower. Guandong electric power, 28:107-109+119.
[11] Qu S. Z, Wu X. H, Sun Q. (2018) Experimental and numerical study on ultimate behaviour of high-strength steel tubular K-joints with external annular steel plates on chord circumference. Engineering Structures, 165:457-70.
[12] Qu S, Wu X, Sun Q. (2018) Experimental study and theoretical analysis on the ultimate strength of high-strength-steel tubular K-Joints. Thin-Walled Structures, 123:244-54.
[13] D'Antimo M, Demonceau JF, Jaspart JP, Latour M, Rizzano G. (2017) Experimental and theoretical analysis of shear bolted connections for tubular structures. Journal of Constructional Steel Research, 138:264-82.
[14] Li X, Zhang L, Xue X, Wang X, Wang H. (2018) Prediction on ultimate strength of tube-gusset KT-joints stiffened by 1/4 ring plates through experimental and numerical study. Thin-Walled Structures, 123:409-19.
[15] Nei X. Z. (2018) Mechanics properties of double-limb-double-plate connections on steel pipe and angle steel. Nan Chang university, Nan Chang.