Influence of diameter thickness ratio of main tube on bearing capacity of steel tube tower joints

Liang Zhang1*, Shifeng Hou2, Chen Chen1, Yake Tang1, Kai Niu1, Haowei Pei1, Yanzhong Ju2 and Tiantian Lin3

1Electric Power Research Institute, State Grid Henan Electric Power Company, Zhengzhou, Henan, 450052, China;
2School of architectural engineering, Northeast Electric Power University, Jilin, Jilin, 132012, China;
3Henan Jiuyu Bohui Ark Consulting Development Co., Ltd, Zhengzhou, Henan, 450000, China.
*Corresponding author’s e-mail: zhangliang13@sgcc.com.cn

Abstract. In order to study the influence of steel tube diameter thickness ratio on the bearing capacity of steel tube angle steel tower joint, the finite element model of tube plate joint was established, and the failure mode and bearing capacity of the joint under different steel tube diameter thickness ratios were studied, and the influence law of steel tube diameter thickness ratio on the bearing capacity of steel tube tower joint was obtained, and the relationship between steel tube diameter thickness ratio and steel tube tower joint bearing capacity was established through regression analysis in this paper. The results show that angel steel tube plate K-type joint has two kinds of failure mode, and in a certain range, the bearing capacity of the joints increases with the increase of the steel tube diameter thickness ratio, and decreases after reaching the maximum bearing capacity.

1. Introduction
Due to the continuous improvement of the voltage level of the transmission line, the height of the transmission tower increases and the load it bears increases, the traditional transmission tower's single angle steel main material can no longer meet the safety design requirements. Double angle steel and steel tube are the types of main members commonly used in the transmission line with higher voltage. The ultimate bearing capacity of the transmission tower can be improved by using the steel tube as the main material instead of the main material of the transmission tower. Using steel tube instead of single angle steel as the main members of transmission tower can not only improve the torsion resistance of main members and joints, but also improve the stability of the structure, thus improving the ultimate bearing capacity of transmission tower. Whitemore [1] studied the elastic stress distribution of Warren truss gusset plate by experiment, and put forward the famous effective width theory. It is found that the stress of gusset plate is mainly distributed in the effective width. Shen et al. [2] carried out systematic experiments on the external gusset plate of steel truss, and studied the stress distribution, strain distribution and its development law on the gusset plate, and summarized the failure mechanism of the gusset plate and the development law of the plastic zone. Brown [3] proposed an analysis model based on Euler equation, which considers the buckling behavior of plates, and classified the bearing capacity

[Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd]
of compression gusset plates as the concept of stability design. Hu [4] carried out the full-scale test of gusset plates, and proved that the main failure modes of gusset plates were global instability and local instability. It was found that eccentric action of gusset plates would significantly reduce the buckling bearing capacity and ultimate bearing capacity of gusset plates, and pointed out that it was sometimes unsafe to check the bearing capacity of gusset plates by effective width method. Korol [5] concluded that most of the specimens failed due to shear lag through the test of rectangular steel tube plate joints. According to the thin-walled cylindrical shell theory, the deformation formula of gusset plate under transverse bending moment was proposed by Li [6] through the research on the joint internal force distribution of four kinds of section tower columns under the action of axial force and additional transverse bending moment. Lutz [7] studied the gusset plate through experimental research and theoretical analysis, and found that the overall instability mainly occurred to the gusset plate, and proposed the design method and measures of the gusset plate. Yu et al. [8] carried out full-scale experimental study on tube plate K-type joints of steel tube tower, discussed the ultimate bearing capacity of the joints, and proposed an analysis model for calculating the ultimate bearing capacity of the joints. Ju et al. [9] carried out the ultimate bearing capacity test of five steel tube tower tube plate K-type joints with stiffeners, and studied the influence of stiffener plate layout on the failure mode and bearing capacity of the joints. Nie [10] put forward the form of steel tube double limb and double plate joint. Through static load experiment and finite element simulation, the difference of mechanical characteristics between tube single limb single plate joint and tube double limb double plate joint was analyzed, and the weak parts of tube double limb double plate joint under fatigue load were obtained. There are no relevant codes and regulations at home and abroad for the design method and formula of the joint of steel tube and angle steel composite tower, and the current research on the angle steel tube plate joint is not very deep.

K-type joint is the most common joint form of transmission tower structure. In this paper, the finite element model of K-type joint of steel tube and angle steel composite tower is established by using the finite element software ANSYS, and the ultimate bearing capacity of the joint is analyzed. The influence of steel tube diameter thickness ratio on the failure mode and ultimate bearing capacity of steel tube plate joint is studied, and the relationship between the ultimate bearing capacity of angle steel tube plate joint and the diameter thickness ratio of steel tube is established.

2. The foundation of finite element model

2.1. Geometry parameters of joint
Considering different thickness of gusset plate, length of gusset plate and diameter thickness ratio of steel tube, 15 groups of joints are designed for ultimate bearing capacity analysis. The thickness of gusset plate is 18 mm, 20 mm and 22 mm respectively, and the ratio of length to thickness is between 32.3 and 45. The thickness of the steel tube is 5, 7, 9 and 11 mm respectively, and the diameter of the steel tube D is taken as 159mm, and steel tube diameter thickness ratio is equal to the ratio of steel tube diameter to steel tube thickness. In order to avoid the influence of the end of the steel tube on the joint area, the length of the steel tube is taken as 950mm which is about 6 times of the diameter of the steel tube. The width of the joint plate is 350 mm, and the angle steel inclined angle is 50°.

2.2. Element selection
In order to simulate the eccentric effect of the pressure from angle steel on one side of gusset plate, the 3D solid element SOLID92 is used for modeling, and the face-to-face contact element conta174 and target element targe170 are used to simulate the interaction between gusset plate and angle steel.

2.3. Material properties and mesh generation
Q235 steel is used for gusset plate and angle steel, with yield strength of 235MPa, elastic modulus of 2.06×10^5MPa/mm² and Poisson's ratio of 0.3. The steel constitutive model is simplified by the multilinear isotropic strengthening model. The 8.8 grade high strength bolt is used, which adopts the
ideal elastic-plastic constitutive model. Both materials comply with von Mises yield criterion and related flow rule, and the model is divided by free meshing. The degree of freedom of node on the junction line between gusset plate and steel tube is coupled, in order to simulate the weld connection of angle steel tube plate K-type joint.

2.4. Boundary conditions and load application
According to the actual stress state of K-type joint in the transmission tower structure, the angle steel is restrained in radial direction, and only has axial displacement. When the influence of steel tube axial force on the ultimate bearing capacity of gusset plate is not considered, one end of steel tube is fixed and the other end is hinged; when the influence of steel tube axial force on the ultimate bearing capacity of gusset plate is considered, one end of steel tube is fixed and axial force is applied at the other end. According to the fact that the angle steel of truss joint is basically under axial compression, the load of the joint is uniformly loaded on the angle steel, and one of the two angle steel is in tension and the other is in compression.

In the process of solution, the step loading method is adopted until the gusset plate is damaged. The Newton-Raphson iterative method is used to calculate the overall buckling load of the gusset plate. When the load of the steel angel tube plate K-type joint is close to the ultimate load, the arc length method is used to calculate the descending section of the load displacement curve of the gusset plate.

3. Failure mode of angle steel tube plate K-type joint
The calculation results of 15 groups of joint models show that when the thickness of gusset plate is 18, 20 and 22 mm, and the thickness of steel tube is 5, 7 and 9 mm, respectively, the K-type joint of angle steel tube plate occurs the instability of steel tube, and the failure mode is lateral deformation of both sides of steel tube as shown in figure 1(a). When the thickness of gusset plate is 18 mm and 20 mm, respectively, and the thickness of steel tube is 11 mm, the gusset plate of angle steel tube plate K-type joint occurs overall instability out of plane. When gusset plate thickness is 18mm, 20mm and 22mm respectively and steel tube thickness is 13mm, the gusset plate of angel steel tube plate K-type joint occurs overall instability out of plane similarly. The specific behavior is the large deformation of gusset plate out of plane, accompanied by certain torsion, and at this time, the angle steel has only a small deformation, which does not reach the instability failure, as shown in figure 1(b). When the thickness of gusset plate is 22mm and the thickness of steel tube is 11mm, obvious plastic deformation occurs at the side wall of steel pipe, and then the out of plane instability failure of gusset plate occurs.

![Figure 1. Failure mode of joint: (a) Steel tube instability mode; (b) Gusset plate instability mode.](image)

4. The relationship between the bearing capacity of angle steel tube plate K-type joint and the diameter thickness ratio of steel tube
Table 1 shows the calculation results of bearing capacity of joints with different parameters. It can be
seen from the calculation results that the ultimate bearing capacity of joints increases with the increase of steel tube thickness, and when joint ultimate bearing capacity reaches the maximum value, it presents a downward trend. This is due to that the increase of the thickness of the steel tube improves the lateral restraint effect of the gusset plate and reduces the deformation outside the plate, thus increasing the ultimate bearing capacity of the joint. When joint ultimate bearing capacity reaches the maximum value, the weak part of angel steel tube plate joint is transferred from gusset plate to steel tube, and the joint ultimate bearing capacity decreases. For the joints with damaged steel tube, under the same steel tube thickness, increasing the thickness of gusset plate can improve the ultimate bearing capacity of the joint to a certain extent. This is due to that the increase of the thickness of the gusset plate makes the steel tube bear the load of the gusset plate in a larger range, resulting in a small increase in the bearing capacity. When the thickness of gusset plate exceeds a certain value, the reduction of diameter thickness ratio of steel tube has little contribution to the bearing capacity. This is due to that the main tube radial stiffness of gusset plate is much greater than that of the main tube, that is to say, the stress distribution of gusset plate is greater than that of main tube. Therefore, when the gusset plate yields in most areas, most of the section of the main tube has not yet entered the plasticity, and the main tube material has not been fully utilized when the gusset plate is damaged. Therefore, the thickness of gusset plate should adapt to the diameter thickness ratio of main tube.

Table 1. The ultimate bearing capacity of angel steel tube plate K-type joint.

| Test number | Steel tube thickness (mm) | Steel tube diameter thickness ratio γ | Gusset plate thickness $t_p$ (mm) | Gusset plate length $L_p$ (mm) | Gusset plate length thickness ratio $L_p/t_p$ | Gusset plate ultimate bearing capacity $P$ (kN) | Joint failure mode |
|-------------|--------------------------|--------------------------------------|-----------------------------------|-------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------|
| 1           | 13                       | 12.23                                | 18                                | 690                           | 38.3                                          | 875                                           | Gusset plate instability |
| 2           | 13                       | 12.23                                | 20                                | 710                           | 35.5                                          | 1022.69                                       | Gusset plate instability |
| 3           | 13                       | 12.23                                | 22                                | 790                           | 35.9                                          | 1129.14                                       | Gusset plate instability |
| 4           | 11                       | 14.45                                | 18                                | 670                           | 37.2                                          | 826.62                                        | Gusset plate instability |
| 5           | 11                       | 14.45                                | 20                                | 750                           | 37.5                                          | 990.8                                         | Gusset plate instability |
| 6           | 11                       | 14.45                                | 22                                | 770                           | 35.0                                          | 1105.34                                       | Steel tube instability and gusset plate instability |
| 7           | 9                        | 17.67                                | 18                                | 770                           | 42.8                                          | 1065.1                                        | Steel tube instability |
| 8           | 9                        | 17.67                                | 20                                | 670                           | 33.5                                          | 1049.92                                       | Steel tube instability |
| 9           | 9                        | 17.67                                | 22                                | 750                           | 34.1                                          | 1183.62                                       | Steel tube instability |
| 10          | 7                        | 22.71                                | 18                                | 810                           | 45.0                                          | 989.45                                        | Steel tube instability |
| 11          | 7                        | 22.71                                | 20                                | 650                           | 32.5                                          | 1007.55                                       | Steel tube instability |
| 12          | 7                        | 22.71                                | 22                                | 730                           | 33.2                                          | 1059.48                                       | Steel tube instability |
| 13          | 5                        | 31.80                                | 18                                | 790                           | 43.9                                          | 841                                           | Steel tube instability |
| 14          | 5                        | 31.80                                | 20                                | 690                           | 34.5                                          | 850.08                                        | Steel tube instability |
Through regression analysis of the calculation results under steel tube instability mode, the fitting curve between joint bearing capacity and steel tube diameter thickness ratio can be obtained, as shown in figure 2, and the decisiveness coefficient $R^2$ of fitting formula is 0.8597, close to 1, which indicates that steel tube diameter thickness ratio has good decisiveness for joint ultimate bearing capacity. The relationship between the ultimate bearing capacity of the joint and the diameter thickness ratio of the steel tube can be obtained as follows:

$$P = 1167.1 + 2.09\gamma - 0.37\gamma^2$$ (1)

Where $P$ is the angle steel tube plate joint ultimate bearing capacity, and $\gamma$ is steel tube diameter thickness ratio which is equal to the ratio of steel tube diameter to steel tube thickness.

Figure 2. The fitting curve between joint bearing capacity and steel tube diameter thickness ratio.

5. Conclusions
In this paper, the finite element model of angle steel tube plate joint is established, and the influence of steel tube diameter thickness ratio on the failure mode and bearing capacity of steel tube tower joint is studied, and the relationship between the steel tube diameter thickness ratio and the bearing capacity of steel tube tower joint is established. The conclusions are as follows:

(1) Under different gusset plate thicknesses and steel tube diameter thickness ratios, the angle steel tube plate joint has two kinds of failure mode which are gusset plate instability and tube instability.

(2) The results of finite element analysis show that the steel tube diameter thickness ratio has a significant impact on the bearing capacity of the steel tube plate joints. With the decrease of the diameter thickness ratio of the steel tube, the ultimate bearing capacity of the joint increases correspondingly. When the bearing capacity of the joint reaches maximum value, the ultimate bearing capacity of the joint shows a downward trend. When the thickness of gusset plate increases to a certain value, the reduction of diameter thickness ratio of steel tube has little contribution to the bearing capacity.

(3) The relationship between the diameter thickness ratio of steel tube and the bearing capacity of angle steel tube plate joint is obtained by regression analysis: $P = 1167.1 + 2.09\gamma - 0.37\gamma^2$, and steel tube diameter thickness ratio has good decisiveness for angle steel tube plate joint ultimate bearing capacity.
Acknowledgments
This research is supported by the State Grid Corporation Henan Electric Power Company Science and Technology Project (No. 5217L0200006).

References
[1] Whitmore, R.E. (1952) Experimental investigation of stresses in gusset plate. Engineering Experiment Station, University of Tennessee.
[2] Shen, Z.Y., Zhao, X.Y. (1987) Study on static behavior of external gusset plate of welded steel truss. Industrial architecture, 8: 19-27.
[3] Brown, V.L. (1988) Stability of gusseted connections in steel structure. Department of Civil Engineering, University of Delaware.
[4] Hu, S.Z., Cheng, J.J.R. (1993) Compressive behavior of gusset plate connections. Structural Engineering Report, University of Alberta, 153.
[5] Korol, R.M. (1996) Shear lag in slotted HSS tension members. Canadian Journal of Civil Engineering, 6:1350-1354.
[6] Li, M.H., Ma, R.L. (2002) Elastic analysis of insert plate connection joint between steel tube tower column and web member. Special Structure, 3: 15-17.
[7] Lutz, D.G., LaBoube, R.A. (2004) Behavior of thin gusset plates in compression. Thin-Walled Structures, 5:861-875.
[8] Yu, S.C., Sun, B.N., Ye, Y., et al. (2004) Experimental study and theoretical analysis of ultimate bearing capacity of high-rise steel tube tower joints. Engineering Mechanics, 3: 155-161.
[9] Ju, Y.Z., Li, J.Y., Wang, D.H., et al. (2018) Study of the Ultimate Load Capacity of K-Type Tube-Gusset Plate Connections. International Journal of Steel Structures, 2: 596-607.
[10] Nie, X.Z.(2018) Analysis of mechanical properties of double leg and double plate connection joint between steel tube main member and angle steel inclined member. Nanchang: Nanchang University dissertation.