Finite Element Analysis and Optimization of the Planar Steel Tubular K-Joints

Ying Chen, Qingtao Yang, Dongchen Wang
State Nuclear Electric Power Planning Design & Research Institute Co., Ltd., 100095, Beijing, China
email: 773603548@qq.com

Abstract. Planar steel tubular K-joints feature various geometric forms and intricate load states, whose bearing capacity is influenced by a number of factors. To address the problems above, a research on the bearing capacity of common planar K-joints in practical engineering projects was conducted. Based on numerical simulation, nonlinear finite element analysis on four kinds of planar K-joints was carried out in ANSYS. The bearing capacity and failure modes of those K-joints were figured out. The bearing capacity of each combination was compared. The results provided by finite element analysis was compared with those derived from codes. The design of K-joints was optimized, thereby improving the bearing capacity and satisfy requirements of engineering projects.

1. Introduction
Given the outstanding mechanical properties of steel tubular members, steel tube towers have been widely used in large span transmission lines and high voltage substation gantries in recent years. K-joints play an integral part in trussed steel structures such as transmission line towers, whose mechanical properties and failure modes directly influence the bearing capacity and safety of the whole structure [1].

The research on planar K-joints dates back to a long time ago. In 1950s, the United States commenced the research on steel tubular joints. In 1970, Eastwood and Wood, two scholars from the United Kingdom, recorded the experimental and theoretical research results of welded joints between rectangular and circular tubes at Sheffield University. The design methods they put forward afterwards were adopted by the design manual for steel tubular structural connections which was published as the first one in the world in 1971. In 1981, International Institute of Welding (IIW) published a new set of failure modes of N, T, Y and X shaped tubular joints, including a great number of theoretical and empirical corrections [2][3].

Chinese standard for design of steel structures (GB 50017-2017) presents calculation methods of K-joints [4]. In this paper, four kinds of K-joints are analyzed respectively based on codes and ANSYS, whose stress characteristics are studied. Their stress states and ultimate bearing capacity are compared in order to identify the joint form with the largest bearing capacity and recommend the optimum joint design scheme for real engineering projects. In the meantime, a parametric analysis of the K-joint with the largest bearing capacity is carried out. The effect of each parameter on bearing capacity is investigated. Eventually, the design scheme for the joint is optimized for the purpose of improving its bearing capacity.
2. Analysis model

2.1. Geometric model of K-joint
This paper focuses on the research of planar K-joints, whose geometric model is schematically represented in Figure 1. The typical combination forms of K-joints mainly include:

i) A circular steel pipe serves as the chord member, which is connected with two circular web members

ii) A circular steel pipe serves as the chord member, which is connected with two square web members

iii) A square steel pipe serves as the chord member, which is connected with two circular web members

iv) A square steel pipe serves as the chord member, which is connected with two square web members

The cross-sectional areas of cylindrical members and square members are designed to be equal in order to facilitate the analyses and comparison of the bearing capacity of various K-joints. The length of the chord member (represented by \( L \) in Figure 1) is 1200mm. The length of the web members (represented by \( L_1 \) and \( L_2 \) in Figure 1) is 500mm. \( \theta_c \) equals 45 degrees. \( \theta_t \) equals 50 degrees. The thickness of the chord member (represented by \( t \) in Figure 1) is 5mm. The thickness of the web members (represented by \( t_1 \) and \( t_2 \) in Figure 1) is 4mm. The diameter of the chord member is represented by \( d \) in Figure 1. The diameters of the web members are represented by \( d_1 \) and \( d_2 \) respectively in Figure 1.

2.2. Boundary conditions and loading modes
Taking into account the requirements of real engineering projects and the stress characteristics of K-joints and referring to extensive domestic data, the model is established combined with the functions of finite element analysis software. The boundary conditions are as follows. The right end of the chord member is fixed. The left end is connected to a sliding support. The ends of two web members are hinged and they are allowed to move along the axes respectively [5].

Two web members are subject to tension and compression respectively. Considering the formulas in design codes, \( N_c \) and \( N_t \) are applied according to the ratio of \( \sin \theta_c \) to \( \sin \theta_t \) until the structure is destructed. The loading condition is shown in Figure 2.

2.3. Element shapes and properties
In the finite element simulation, the elastic-plastic shell element with three dimensions and four nodes is selected in ANSYS. Each element has four nodes and six degrees of freedom, which include displacement in three directions and rotation in three directions. The nonlinear function of Shell 181 shell element are applied, such as large deformation and stress stiffening [6].

2.4. Material properties
Q355 steel with the yield strength \( f_y \) of 345mpa, elastic modulus \( E \) of \( 2.06 \times 10^5 \)MPa and Poisson's ratio \( \nu \) of 0.3 is applied in this model. The material is idealized to be elastic-plastic and comply with Von-
Mises yield criterion. The material is considered as bilinear isotropic strengthening. The Newton Raphson iterative method and the arc length method are combined to establish a nonlinear equilibrium solution method. The influence of initial stress, deformation, residual stress and weld on the ultimate bearing capacity of the joint is not taken into consideration [7].

2.5. Meshing
In the finite element analysis of steel tubular joints, time and accuracy of ANSYS nonlinear calculation depend on the degree of mesh refinement. By controlling the side length of the element, the element size of the chord member close to the intersection area of the chord member and the web member basically equals the thickness of the chord member. The element size of the chord member and web members far away from the intersection area is twice the thickness of the members respectively. Furthermore, the intersection lines of the chord members and web members are refined locally to enhance the density of the mesh [8].

3. Comparison and analyses of joint stress

3.1. Process of joint stress
In the process of loading along the axial direction of the web members, the local bulge occurs to the end of the compressive web member close to the chord member and necking deformation takes place at the end of the tensile web member. The part of the chord member connected with the compressive web member is concave inward and the part connected with the end of the tensile web member is convex outward.

When loads are imposed through the web members, the stress distribution along the axial and circumferential direction of the chord member is apparently uneven due to the fact that the intersection lines of the joint are complex and the radial stiffness of the chord member is significantly different from its axial stiffness. Moreover, local deformation and stress concentration emerges at the intersection lines, while the stress decreases rapidly away from the intersection lines. The circumferential stress at the saddle points or crown points of the joint is the largest, where yield takes place first. However, it does not mean that the joint is destructed immediately at this moment. With the increase of the loads, the plastic zone gradually forms, which results in stress redistribution. Afterwards, the plastic zone constantly expands. The joint eventually fails when significant local plastic deformation occurs [9].

According to the stress cloud chart, when the loads are low, the intersection area between the chord member and the web member starts to yield. With the load increasing, the plastic zone extends outward along the cross section of the chord member. When the joint fails, most of the section of the chord member within the intersection area is in the state of plasticity and the plastic zone has extended to the cross section far away from the intersection area. The final stress result is shown in Figure 3.
3.2. Judgment of ultimate bearing capacity

For the joints where members are mainly subjected to axial loads, their ultimate bearing capacity is identified on the basis of three criteria as listed below.

i) the ultimate strength criterion: Load vs. deformation curve is plotted based on the axial force of the web member and the deformation of the chord member pipe wall along the axis of the web member. The crest of the curve is taken as the ultimate bearing capacity.

ii) the ultimate deformation criterion: The deformation of the chord member pipe wall along the chord member direction reaches a certain limit value. In the world, the ultimate bearing capacity is commonly identified on the basis of the load which makes the deformation of the chord member pipe wall in the direction of the web member reach 3% d.

iii) The ultimate bearing capacity is identified on the basis of the load which makes the strain on the surface of tensile web member or in the intersection area of members reaches 20% $\varepsilon$ ($\varepsilon$ represents the ultimate tensile strain of the material).

In this paper, the ultimate bearing capacity is identified in accordance with the ultimate strength criterion. The crest of the load vs. displacement curve is taken as the ultimate bearing capacity as shown in Figure 4. The results of different joint types are shown in Table 1.
Table 1 Bearing capacity for different joints

| Groups | Joint types | d/ mm | d₁=d₂/ mm | Bearing capacity/kN | Nc₁/ Nc₂ |
|--------|-------------|-------|-----------|---------------------|---------|
|        |             |       |           | Finite element Nc₁ | National codes Nc₂ |
| 1      | A           | 273   | 159       | 296.1               | 242     | 1.22 |
|        | B           | 273   | 126       | 271.4               | /       | /    |
|        | C           | 215   | 159       | 192.0               | 237     | 0.81 |
|        | D           | 215   | 126       | 174.1               | 239     | 0.73 |
| 2      | A           | 273   | 180       | 418.5               | 310     | 1.35 |
|        | B           | 273   | 142       | 327.0               | /       | /    |
|        | C           | 215   | 180       | 257.1               | 268     | 0.96 |
|        | D           | 215   | 142       | 216.3               | 270     | 0.80 |
| 3      | A           | 300   | 159       | 286.7               | 219     | 1.31 |
|        | B           | 300   | 126       | 264.1               | /       | /    |
|        | C           | 237   | 159       | 187.2               | 226     | 0.83 |
|        | D           | 237   | 126       | 184.7               | 228     | 0.81 |

Note: There is no calculation formula in national codes for the K-joint composed of square chord member and circular web members.

Bearing capacity of three groups of joints are listed in Table 1. On the basis of the premise that the square members have the same cross-sectional area with the circular counterparts, the ultimate bearing capacity of Joint Type A, which is composed of a circular chord member and two circular web members, is the highest and that of Joint Type D, which is composed of a square chord member and two square web members, is the lowest. The difference between these two types of joints is approximately 36% to 45%. The finite element calculation result of Joint Type A is 1.22 to 1.35 times that derived from national codes. The finite element calculation result of Joint Type C is 0.81 to 0.96 times that derived from national codes. The finite element calculation result of Joint Type D is 0.73 to 0.81 times that derived from national codes. It is shown that the result derived from codes is conservative for Joint Type A. On the other hand, the results based on codes are unsafe for Joint Types C and D, which should be adjusted properly.

4. Parametric analyses for K-joints

Parametric analysis is carried out for the joint in between a circular steel chord member and two circular steel web members. Combined with the formulas in codes, the effect of each parameter on bearing capacity is studied.

4.1. The effect of the ratio between the diameters of the web members and the chord member β₁

As shown in Figure 5, with the increase of the ratio β₁ = d₁ / d (the outer diameter of the chord member d remains unchanged and that of the web member d₁ increases), the extent of stress concentration in the intersection area of the joint dwindles, while the ultimate bearing capacity of the joint rises. The tendencies indicated by the finite element analysis and code calculation are consistent.
4.2. The effect of the ratio of diameter to thickness of the chord member $\gamma$

As shown in Figure 6, with the ratio of diameter to thickness of the chord member $\gamma = d/t$ increasing (the outer diameter of the chord member $d$ remains unchanged, but the thickness $t$ decreases), the bending rigidity of the chord member decreases and the bearing capacity of the joint diminishes. The finite element analysis suggests the same relationship between $N_c$ and $\gamma$ with the calculation based on codes.

4.3. The effect of the thickness of the web member $t_1$

As shown in Figure 7, with the thickness $t_1$ of the web member increasing, the finite element analysis suggests that the bearing capacity of the joint changes slightly, while code calculation indicates the bearing capacity remains unchanged. The conclusions drawn from two methods are similar.

4.4. The effect of angle between the web member and the chord member $\theta_c$

As shown in Figure 8, with the increase of $\theta_c$, the finite element analysis suggests that the bearing capacity of the joint rises first and falls thereafter and the change is moderate. However, the results derived from codes denotes that the bearing capacity plunges with the increase of $\theta_c$.

4.5. The effect of the axial compressive stress of the chord member

As shown in Figure 9, finite element analysis and results from codes both suggest that the bearing capacity of the joint diminishes with the axial compressive stress of the chord member $\sigma$ increasing.
5. Optimization for steel K-joints

The optimization analysis is carried out for the joint whose chord member and web members are all circular steel pipes. The optimized K-joint is shown in Figure 10. A gusset plate, two insertion plates and two annular plates are incorporated into the joint. The gusset plate and annular plates are welded to the chord member. The insertion plates are welded to web members. The gusset plate and insertion plates are connected with bolts. The chord member diameter $d$ equals 273mm and the web member diameters $d_1=d_2=159$mm, which is consistent with the geometric parameters of Joint Type A in Table 1.

The finite element analysis is conducted for the optimized K-joint. Loads are applied in the same way with Joint Type A. As a result, the stress is shown in Figure 11. With the increase of loading, the web member of the optimized joint reaches its ultimate bearing capacity first, which means that the load cannot be increased any more. The load at this moment is deemed to be the ultimate bearing capacity of the joint, which equals 594.5kN on the basis of computation. The ultimate bearing capacity of the optimized K-joint is twice that of the K-joint of the same specification, which is more competent in the engineering projects with a higher requirement of bearing capacity.

6. Conclusions

On the basis of ANSYS non-linear finite element analysis, this paper brings forward the optimization of planar K-joints. The conclusions drawn from the research are as below.

(1) The majority of the intersection area between the web members and chord member yields when the planar K-joints fail. The failure mode of the joints is primarily plastic failure of the chord member pipe wall.
(2) The joint comprised of a circular chord member and two circular web members boasts the highest bearing capacity. On the other hand, the lowest bearing capacity is present at the joint composed of a square chord member and two square web members. The difference approximates 40%. The finite element analysis result is 1.22 to 1.35 times that derived from codes for the joint whose chord member and web members are all circular. The finite element analysis result is 0.81 to 0.96 times that derived from codes for the joint which is composed of a square chord member and two circular web members. The finite element analysis result is 0.73 to 0.81 times that derived from codes for the joint in between a square chord member and two square web members. It is shown that the bearing capacity derived from codes is conservative for the joint whose chord member and web members are all circular. Nevertheless, the values of bearing capacity based on codes are unsafe for the joints whose chord member is square and web members are square or circular. Correspondingly, adjustments should be made properly.

(3) The ultimate bearing capacity of K-joints primarily depends on the outer diameter ratio of the web member to the chord member $\beta_1$, the ratio of the chord member diameter to its thickness $\gamma$, the axial compressive stress $\sigma$ of the chord member. Namely, the factors above play an important part in the destruction of K-joints. On the other hand, the thickness of the web member $t_1$ and the angle between the web member and the chord member $\theta_c$ exert a slight influence on the bearing capacity of the joints. The results derived from codes and the finite element analysis differ with respect to the influence of $\theta_c$ on the bearing capacity of K-joints. Therefore, it is necessary to do further research on the relationship between bearing capacity and $\theta_c$ and correct the calculation equations provided in codes.

(4) The bearing capacity of the K-joint optimized with a gusset plate and insertion plates is twice that of the K-joint of the same specification. Hence, the optimized K-joint is more adequate to the projects with a higher requirement of bearing capacity.

References
[1] Li Maohua, Xing Haijun, Hu Xiaoguan, et al. 2013 Research on load-carrying capacity of smaller angle k-joints for power transmission steel tubular tower (Building Structure issue 5 2013) pp 48-53.
[2] Hu Xiaoguang, Yang Jingbo, Li Maohua, et al. 2011 Rib Stiffener Distribution and Ultimate Strength of Steel Tubular Tower's K-joint (Science & Technology Review vol 29 No. 26) pp 50-56.
[3] Zheng Boxing and Huang Changhua 2008 Finite Element and Design Method Analysis of Ultimate Strength of Tubular Kt-Joints (Steel Construction vol 23 No. 7) pp 42-47.
[4] Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2017 Standard for design of steel structures.
[5] Wan Haiying and Xie Yufang 2006 Finite element analysis of the ultimate capacity of overlap tubular K-joints (Journal of Hefei University of Technology: Natural Science vol 29 No. 4) pp 478-481.
[6] Chen Yu and Tang Jumei 2011 Experimental research and finite element analysis of bearing capacity of K-joints with circular chord and square braces (Journal of Building Structures vol 32 No. 10) pp 56-64.
[7] Zhang Hong, Pan Ying, Ma Chungang, et al. 2013 Finite Element Analysis of Bearing Capacity of Planar K-Joints (China Science and Technology Information No. 22) pp 57-59.
[8] You Jun, Li Zhengliang, Bai Qiang, et al. 2010 A Study of Influence of Tubular Axial Force on Ultimate Strength of Steel Tubular K-joints (J Chongqing Technol Business Univ. Nat Sci Ed vol 27 No. 3) pp 292-297.
[9] Qin Linxiao, Pan Ying and Zhang Pengju 2014 Bearing Capacity Research of Multi-Planar KKT-Joints Based on ANSYS (Light Industry Machinery vol 32 No. 4) pp 13-17.
[10] Chen Xin 2014 Study of Ultimate Strength Experimental and Calculation Method of Steel Tubular K-joints Considering Negative Eccentric (Beijing Jiaotong University).