

Review of Research Progress on Bearing Capacity of Steel Pipe Joints

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Abstract: This paper summarizes the research progress of rectangular steel pipe or round steel pipe joints in recent years. This paper makes a comprehensive analysis from round steel pipe, square steel pipe and square steel tube. Through experimental study and finite element model analysis, the effects of the geometric parameters such as the main branch diameter (side length) β , the main section diameter (side length) and the branch wall thickness γ , and the τ on the ultimate bearing capacity and the seismic performance of the node are discussed. The study shows that the reasonable diameter, wall thickness and pipe length of the main and branch pipes can significantly improve the ultimate bearing capacity and seismic capacity of the steel pipe node.

Keywords: Steel Pipe Node; Ultimate Bearing Capacity; Seismic Performance; Finite Element Analysis.

1. Introduction

In recent years, with the rapid development of urbanization in China, high-rise buildings can be seen almost everywhere, and the number of large-span buildings and super high-rise buildings, which are generally landmarks, has gradually increased, such as the Bird's Nest in Beijing, the Green Space Center in Wuhan, and the Zhuhai-Hong Kong-Macao Bridge. In this environment, more and more buildings use steel tube structure, such as: gymnasium, airport, station, warehouse, etc., so the steel tube structure has also been greatly developed. Round steel tube and square steel tube are the most common forms of steel tube structure. Round steel pipe is a kind of steel with open ends, hollow and concentric circular section. Compared with other types of steel, round steel pipe has the characteristics of closed section, arbitrary symmetry of section, large stiffness, beautiful appearance and so on. In addition, the cross section of the round steel pipe is symmetrical, and the moment of inertia of the cross section of each axis is the same, so the round steel pipe has good compression and torsion resistance. Square steel pipe usually refers to the steel with open ends, hollow and square section. Compared with other types of steel, the square steel pipe has the characteristics of light weight and good economy when the bending and torsional strength are the same. In addition, the square steel pipe also has many other advantages: (1) it has most of the advantages of round steel pipe, such as symmetrical section, beautiful appearance, etc.; (2) the form is simpler, the construction is more convenient, and more choices can be provided when the building is arranged; and (3) the form is diversified, the appearance and the inner wall are smooth and flat, and various requirements of people on the appearance can be greatly met. Because of these characteristics of steel pipe, steel pipe structure also has the characteristics of strong space, good integrity, large stiffness, light weight, beautiful, simple and so on. As the connection component in the steel tube structure, the steel tube joint bears the load in the plane and out of the plane, the destruction of the joint will generally lead to the overall destruction of the building structure, and the performance of the structure is directly related to the overall safety of the structure, so the steel tube joint occupies an extremely important position in the design of the steel tube structure. There are many joint

forms of steel tube structure, such as X type, K type, Y type, T type, N type and so on. In practical engineering, the most commonly used forms of steel pipe joints are the main round and branch round steel pipe joints whose branch pipes and main pipes are composed of round steel pipes and the main square and branch square steel pipe joints whose branch pipes and main pipes are composed of square steel pipes. However, there are some special advantages for the joint of square steel tube and circular steel tube with square steel tube in the main pipe and circular steel tube in the branch pipe. (1) Compared with the main round steel pipe node, the main square round steel pipe node can be welded with the main pipe only by cutting the branch pipe simply, while the round steel pipe node can be welded with the main pipe only by cutting the branch pipe complicatedly under the same condition, so the square round steel pipe node is simpler and more economical than the round steel pipe node; (2) Compared with RHS joints, RHS joints have lower stress concentration level [2]. In addition, because there are no additional stiffening parts in the main square and support round steel pipe joints, it also has the advantages of convenient connection and less steel consumption.

2. Research Status at Home and Abroad

The research on the static behavior of traditional tubular joints can be summarized into two aspects: bearing capacity and stiffness. Because of the extensive application of steel pipe truss in practical engineering, and in these structures, the branch pipe connected with the tubular joint is mainly subjected to axial force, the earliest research on the static performance of T-shaped, K-shaped and other simple plane tubular joints is mostly carried out. Later, in order to meet the needs of architectural performance, structural stress, manufacturing and construction technology, there are more and more studies on joint deformation performance, hysteretic performance, fatigue performance, reinforced joint performance, fracture resistance performance and complex spatial tubular joints, including joint failure mechanism, joint flexibility, weld bearing capacity, stress and strain, energy dissipation and so on.

2.1. Research Status of Tubular Joints

The research history of tubular joints is relatively long in all kinds of cross section tubular joints, the accumulated research data is more, and the research results are more mature. It is reported that the earliest research on plane circular steel tubular joints was the ultimate strength test of steel tubular joints carried out by the former West Germany in 1948. In the 1950s, the United States began to study the tubular joints of circular steel tubes. Since the 1960s, the research on tubular joints has been carried out in many countries. From the late 1960s to the early 1970s, the design codes of some countries and regions began to incorporate the design of circular tubular joints, and during this period, the application of circular tubular structures in building structures began to increase slowly. In the 1990s, the research and application of tubular structures and their joints became more and more extensive and in-depth. In 1984, Kurobane [3] considered that it was unreasonable to calculate the ultimate bearing capacity of joints by pure theoretical methods, and by using regression method, the experimental results of 73 X-shaped tubular joints, 50 T-shaped tubular joints and 398 K-shaped tubular joints were arranged, and the formula for calculating the strength of tubular planar joints was proposed. The formula can cover the calculation of the bearing capacity of circular tubular joints with the diameter of the main pipe ranging from 60 mm to 510 mm and the yield point of steel ranging from 270 MPa to 500 MPa, and has become the basis for the formulation of design guidelines by the Architectural Society of Japan and the International Committee for Research and Development of Tubular Structures. Lee and Wilmschurs [4] carried out numerical simulation on multi-plane hollow circular tubular K-joints in 1994. Through the analysis and study of the results, the ultimate strength calculation formula of multi-plane hollow circular tubular K-joints was given. In 1996, Lee and Wilmshurst [5] established a finite element model for spatial KK-shaped joints considering geometric and material nonlinearity, and obtained the ultimate bearing capacity of the joints, which laid the foundation for the study of the bearing capacity of spatial joints at that time. In 1998, Kang et al. [6] carried out experimental research and theoretical analysis on the bearing capacity of spatial TT-shaped circular tubular joints with compression on the chord. The test results showed that the axial compression on the chord significantly reduced the ultimate bearing capacity of the joints, but the finite element analysis underestimated the reduction of the bearing capacity of the joints caused by the axial compression on the chord. In 1999, Dexter and Lee [7-8] carried out finite element simulation and loading test on hollow circular tubular K-joints, and gave the parametric equation of static strength of hollow circular tubular K-joints. In 2001, Chen Yiyi et al. [9] carried out an experimental study on four X-type joints with different types of hollow circular tubular joints, and found that there are two main reasons for the failure of X-type joints with hollow circular tubular joints: (1) the plastic deformation of the main pipe is too large; (2) the tensile weld cracks, and for different types of joints, their failure modes are completely different. In 2003, Chen Yiyi et al. [10] took K-type, XK-type and TK-type hollow circular tubular joints as experimental research objects, carried out static loading on them, and took the corresponding load when the displacement of the joint reached 0.005 times of the diameter of the main pipe as the ultimate load of the joint. By analyzing the test results, it was found that in K-type, XK-type, When the two tubes in the K-

plane of the tubular TK joints are the main loaded tubes, the spatial effect should be considered. In addition, the modified formula of the bearing capacity of the tubular TK joints is given. In 2006, Gho et al. [12-14] carried out parametric analysis on 1296 fully overlapped N-shaped circular tubular joints, and conducted in-depth research on the failure mode and failure mechanism of the joints. In 2008, the scholar proposed a parametric formula for the bearing capacity of the above types of joints, and pointed out that the constraints at the end of the joints and the stress of the chord would not significantly affect the bearing capacity of the joints. In 2006, Tong Lewei and Chen Zhuo [15] carried out a static experimental study on a spatial KTT-shaped tubular overlapped joint with all branches welded along the perimeter of the intersection line of the joint and a spatial KTT-shaped tubular overlapped joint with the overlapped branches partially welded along the perimeter of the intersection line. The failure modes, load-deformation curves, strain and stress distributions, and ultimate strength of the two joints were compared and analyzed. The results show that the difference of welding methods has little effect on the ultimate strength of the joints, but leads to the inconsistency of the failure modes of the joints. In 2010, Chen Yu et al. [16] carried out finite element analysis on the overlapped hollow circular tube KT-type joint, studied the whole process of deformation and failure of the specimen and the final failure mode of the specimen, and derived a parameter formula to calculate the ultimate bearing capacity of the overlapped hollow circular tube KT-type joint. In 2017, Lan et al. [17] carried out experimental tests on high-strength steel hollow circular tubular X-joints, and compared the experimental results with the design strength calculated in the current CIDECT code and EN 1993-1-8 code. It is found that the CIDECT specification is more accurate than the EN 1993-1-8 specification in the design of high strength steel hollow circular tubular X-joints. In 2019, Hu Xibing, Liu Xueyao et al. [18] used finite element numerical simulation to study the mechanical properties of high-strength steel N-type lap joints, analyzed the influence of failure mode, geometric parameters and chord axial force on the ultimate bearing capacity of joints, and compared the simulation results with the current code, and proposed a formula for the correction factor of the bearing capacity of joints. In 2020, Qian et al. [19] carried out static loading experimental study and finite element analysis on the hollow circular tube X-shaped joint with larger wall thickness as the research object, and proposed the calculation formula for the ultimate bearing capacity of the thick-walled hollow circular tube X-shaped joint through the analysis of the test results and finite element parameters. In 2020, Shang Renjie et al. [20] carried out finite element analysis on the axial force of the branch pipe of the T-shaped tubular joint of the circular steel tube, and concluded that when the branch pipe of the tubular joint is subjected to axial force, the relationship between the local deformation of the joint and the axial force of the branch pipe is linear at the initial stage, and the overall analysis of the structure can be considered as linear elasticity.

2.2. Research Status of Square Tubular Joint

The production and application of square steel pipe is later than that of round steel pipe. Square steel pipe began to appear in Britain in the 1950s. However, as a structural member, the square steel tube also has its own unique advantages: as far as the mechanical performance of the section is concerned, it

basically has all the advantages of the circular tube, because only the end face of the connecting rod needs to be cut flat, the processing and manufacturing of the connection node between the square steel tube sections is much easier than that of the circular tube node. Of course, although it is easy to manufacture, the load transfer is very complex because of the uneven stiffness distribution in the corner and middle area of the joint section, and the uneven degree of stress distribution in the joint section is more than that in the circular tube section. Similarly, domestic and foreign scholars have carried out a large number of theoretical and experimental studies on square tubular joints, and have achieved very fruitful results, which have been widely used in engineering practice. In 1982, Packer et al. [21] conducted an experimental study on hollow square K-joints, established a plastic model for them, and derived a parameter equation for calculating the ultimate bearing capacity. The accuracy of the parameter equation was verified by comparison. In 2000, Zhao [22] took the cold-formed hollow square T-joint as the research object and carried out the loading test on it. The results showed that the β value had a greater impact on the ultimate displacement of the joint, and proposed the calculation formula of the ultimate bearing capacity of the joint under two failure modes. In 2004, Wu Zhenyu and Zhang Yaochun [23] established a nonlinear finite element analysis model for T-shaped RHS joints with equal section widths of main and branch tubes, and investigated the failure modes of the joints under different geometric parameters and different compression levels of the main tube axis, as well as the influence of the above factors on the static performance of such joints. At the same time, the formulas for calculating the bearing capacity of RHS T-joints with the same section width of main and brace in Chinese Code for Design of Steel Structures (2003 edition) are compared with the formulas in foreign codes or design guidelines and the results of nonlinear finite element analysis. The results show that the formulas in Chinese code are reasonable and feasible. In 2008, Wu Zhenyu et al. [24] conducted an experimental study on the hysteretic behavior of hollow square T-joints, and obtained the failure mode and hysteretic curve of the joints. It was found that the failure of the joints was due to the excessive deformation of the compression joints of the branch pipes under reciprocating loads, and the cracks at the welds of the tension joints. In 2009, Moazed et al. [25] carried out finite element analysis on thin-walled hollow square T-joints subjected to in-plane bending. The analysis results showed the maximum stress position of the joint, and the calculation formula of bending stiffness was given according to the finite element analysis results. In 2009, Shao Yongbo et al. [26] carried out finite element numerical simulation and dynamic test on the square T-joint with thickened main pipe wall, and found that the hysteretic performance of the joint with thickened main pipe wall is better than that of the ordinary joint. In 2017, Lv Yuxia and Shao Yongbo [27] also studied hollow square tube T-joints under high temperature, and carried out experimental research and finite element analysis. In 2017, Chen Hengchao et al. [28] applied cyclic loading to four hollow square tube T-joints with inner diaphragms to study their seismic performance. In order to compare, two ordinary square tube T-joints were designed. Through comparison, it was found that the addition of inner diaphragms could significantly increase the ultimate bearing capacity of the joints, and the seismic performance of the joints could also be improved. In 2017, Xia et al. [29] carried out numerical simulation and experimental research in order

to study the axial hysteretic behavior of square T-joints reinforced by double-layer plates, discussed the hysteretic curve, skeleton curve, energy dissipation capacity, ductility, strength and hysteretic mechanism of the joints, and analyzed the influence of double-layer plate reinforcement on the hysteretic behavior of the joints. It is found that the double-layer plate reinforcement can effectively prevent the occurrence of cracks, ensure the integrity of the tube, and improve the strength of the joint, but the energy dissipation capacity and ductility of the joint will be somewhat reduced. It is also shown that the ratio of the width of the branch pipe to the chord pipe and the ratio of the width of the double-layer plate to the chord pipe are the key parameters affecting the load transfer mechanism and failure mode of the joint. In 2018, Chen Yadong et al. [30] applied axial pressure and cyclic load to the branch pipe of hollow square T-joint with β value of 0.4 and 0.8, and analyzed the influence of β value on the hollow square T-joint. The results showed that the square T-joint with β value of 0.4 and 0.8 was buckling failure of the main pipe under axial pressure, while it was tearing failure of the joint under cyclic load.

2.3. Research Status of Square and Round Steel Tube Joints

The square and round steel pipe node is a general term for the node with the main pipe being square pipe or rectangular pipe and the branch pipe being round pipe (referred to as "square main pipe and round branch pipe node") and the node with the main pipe being round pipe and the branch pipe being square pipe or rectangular pipe (referred to as "round main pipe and square branch pipe node"). In the traditional steel tube truss structure, the main tube and branch tube are usually designed as the same type of section, that is, both of them are circular tubes or rectangular (square) tubes. For the various forms of joints, scholars at home and abroad have carried out a lot of research, and formed a more systematic calculation method of bearing capacity. However, there are few researches on the joints with square chord and circular branch and the joints with square chord and square branch.

In 2001, Liu Jianping et al. [31-33] carried out finite element analysis of K, T and Y-shaped circular steel pipe joints by using ANSYS software, investigated the mechanical properties of the joints, obtained the failure forms, ultimate bearing capacity and plastic development of the joints, deeply analyzed the law of influence of geometric parameters on the mechanical properties of the joints, and proposed the reinforcement method of the joints on this basis. However, the research is based on finite element analysis, and no experimental research has been carried out.

In 2003, Mashiri and Zhao [34] conducted in-plane static bending tests on T-shaped joints of thin-walled hollow and square steel pipes. The results showed that the joint failure was due to the buckling of the main pipe surface. After large deformation, the main pipe cracked, causing these joints to reach peak load, and a joint yield line model was established. Based on the plastic mechanism analysis of yield line theory, a formula for calculating the ultimate strength of T-shaped joints of hollow and square steel pipes is derived. It is also shown that there is a good agreement between the predicted ultimate strength and the experimental ultimate strength.

In 2004, Wan Haiying et al. [35] used Nastran to conduct elastoplastic large-deflection numerical simulation analysis of Y-shaped circular intersecting pipe joints, understand the

displacement change and stress distribution of intersecting joints at each loading stage and the development of plastic zone during the whole loading process, and investigate the failure forms of intersecting joints. The relative theory of orthogonal experimental design is introduced to quantitatively analyze the Y-shaped square and square intersecting joints, and the variation law of ultimate bearing capacity and geometric parameters is obtained. The research on the node mainly focuses on the parameter analysis and does not compare with the calculation result of the standard formula.

In 2010, Chen Yu and Tang Jumei [36] carried out finite element numerical simulation with K-shaped joints of hollow circular steel pipe. The results showed that the ultimate load of hollow circular steel pipe K-shaped joints was greatly influenced by γ value and τ value, while the β value was relatively small. The parametric equation for calculating the ultimate load of the joints was also fitted, and its rationality and accuracy were verified.

In 2011, Chen Yu and Tang Jumei [37] conducted experimental research and finite element analysis on K-shaped joints of hollow and square steel pipes. The research showed that increasing the wall thickness of branch pipes could change the failure mode of joints. The bearing capacity calculation formulas of circular and square K-shaped joints in current norms were not applicable to K-shaped joints of circular and square steel pipes, and the experimental results were greater than the calculated values of the formulas.

In 2011, Deng et al. [38] carried out finite element simulation on KT shaped joints of circular steel pipes. Based on the analysis of experimental data, a formula was given to calculate the bearing capacity.

In 2012, Shu Xingping [39] used finite element software to verify the failure mode, deformation process and bearing capacity of 8 N-shaped main square branch circular lap steel pipe joints and 2 gap steel pipe joints, analyzed the influence of geometric parameters on the ultimate bearing capacity, and concluded that the inner concealed part was not welded and had little influence on the bearing capacity of joints under pressure from the lap branch pipe. At the same time, multiple linear regression method is applied to fit the revised calculation formula of the bearing capacity in the code. In particular, it is pointed out that the calculation formula of the bearing capacity of the joint of the N-shaped square branch pipe in the current code at home and abroad is not applicable to the local buckling failure mode of the main pipe. Moreover, the formula does not take into account the influence of factors such as whether the inner concealed part is welded or not, the nature of the branch pipe axial force and the main shaft force, etc., so it needs to be improved.

In 2013, Tong et al. [40] took T-shaped joints of hollow and square steel pipes as the research object, conducted tests and finite element simulation, and analyzed the stress distribution of joints at the weld.

In 2015, Wang Wei et al. [41] conducted an experimental study on the axial tensile properties and strength of X-shaped joints of hollow and circular steel pipes with 5 non-rigid connections and 3 rigid connections, and proposed a formula for predicting weld strength according to the effective length, which also proved that the formula met the reliability requirements of the AIC-LRFD method. The study mainly focused on the tension of joint welds. No studies were carried out under tube pressure.

In 2016, Yang Wenwei et al. [42] numerically analyzed the

influence of geometric parameters such as lap rate OV , diameter-width ratio β of main square branch, thickness ratio τ of main branch, width-thickness ratio γ of main branch and Angle θ of main branch on the ultimate bearing capacity of such joints, and obtained the influence law of each parameter on the bearing capacity of joints.

In 2017, Guo Teng [43] for the first time studied and analyzed the hysteretic performance, ductility, stiffness and energy dissipation capacity of the joint reinforced by circular K-type main pipe grouting concrete with main square support. Secondly, the mechanical properties of K-type square joints under two different strengthening modes of the main pipe wall with casing and the main pipe with concrete grouting are compared by variable parameters, and the ultimate bearing capacity of the joint is the best strengthening measure.

In 2018, Yuan Zhishen [44] studied the ultimate bearing capacity of the N-shaped main square branch circular lap joint under the influence of the main shaft force, established a finite element model based on the test, calculated the parameters of the influence of the main shaft force on the joint, and compared the calculation results with the current standard formula. The suggested formula of the influence parameter of the main axial force on the bearing capacity of the N-shaped main square branch circular lap joint is presented.

In 2021, Yuan Zhishen and Gan Yu et al. [45] studied the relationship between the static properties of the gap joints of N-shaped main square-supported round steel pipes and the mechanical properties of the lap joints, conducted a comparative test between the gap joints of N-shaped circular steel pipes and the lap joints, and found that the bearing capacity of the gap joints was lower than that of the lap joints of the same diameter. The linear regression method is used to fit the modified calculation formula of bearing capacity in the present line specification.

In 2021, Li Xueting et al. [46] conducted an ultra-low cycle fatigue test on X-shaped square steel pipe, studied the failure mode of joints, analyzed the strain distribution law at joints, and obtained the fatigue life of joints. They found that joints with stiffeners in the main pipe had poor deformation ability and showed the characteristics of tensile fracture failure.

Packer[47] first proposed in his doctoral thesis in 1978 that: Since the ratio of section circumference and area of square and round pipes with the same side length and diameter is $\pi/4$ when the wall thickness is thin, when calculating the bearing capacity of round branch pipe joints of square pipes, the size of round branch pipe can be multiplied by $\pi/4$ to convert into equivalent square pipe size, and then the bearing capacity calculation formula of square pipe joints can be substituted. However, when this concept is applied to the semi-empirical design formula in national norms, it is not the size of the round pipe multiplied by $\pi/4$ to convert the equivalent square pipe size into the bearing capacity of the joint of the square pipe, but directly assume that the side length of the square pipe is the diameter of the round pipe. The bearing capacity of square branch pipe joints is obtained by substituting the bearing capacity formula and multiplying by $\pi/4$. Moreover, there is no comparison of test data in a large number of specifications and design guidelines that adopt this "branch conversion method" [48].

3. Conclusion and Prospect

To sum up, in recent years, domestic and foreign scholars have carried out a large number of experimental studies and

theoretical analyses on the mechanical properties of tubular joints, but the studies mainly focus on joints where the main and branch pipes are both round or rectangular, and mainly focus on finite element parameter analysis, and their mechanical properties and experimental studies are scarce.

Compared with the research of circular pipe joints and rectangular pipe joints, the research of main square-supported round steel pipe intersecting joints at home and abroad is not sufficient. Especially in the joint bearing capacity calculation, the bearing capacity calculation formula of the joint intersecting the main square-supported round steel pipe directly uses the simple geometric relationship between the thin-walled round pipe and the thin-walled square pipe, and locally modifies the bearing capacity calculation formula of the rectangular pipe joint, but the formula has not been verified by enough tests. From the existing research results, the joint bearing capacity calculated in this way is sometimes too conservative, and sometimes too unsafe. On the one hand, the advantages of the intersecting joints of the main square supported round steel pipe cannot be fully utilized, on the other hand, the safety and reliability of the design cannot be fully guaranteed, so the popularization and application of the main square supported round steel pipe structure is limited.

Therefore, it is an urgent problem to study the branch transformation method of the main square and branch circle intersecting joints, and it is also an important topic to further improve the current design specification.

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