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A Review of the Research Progress on Hysteretic Behavior of Steel Tubular Intersecting Joints

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Abstract

Steel tubular structures is widely used in large-span public buildings and mid to high rise buildings, and tubular intersecting joints is one of common form of joint in steel tubular structures. The main research results on the hysteretic behavior of three kinds of tubular intersecting joints internationally is reviewed in the paper,including ordinary tubular intersecting joints,reinforced tubular intersecting joints,and high-strength steel intersecting joints. and based on these research, propose several opinions for further research on the hysteretic behavior of steel pipe joints.

Keywords

Tubular Intersecting Joints; Hysteretic Behavior; Research Progress; Literature Review.

1. Introduction

Since the 21st century, the vigorous development of the construction industry, steel pipe structure with its light weight, high strength, beautiful shape, good plastic toughness, long service life and other advantages, in the modern industrial construction shine, more and more widely used in a variety of high-rise buildings, large span space structure.

Steel pipe joints is an important part of the steel pipe structure. The choice of the joints has a direct impact on the mechanical performance of the structure, the project cost and the construction and installation. Because of its simple structure and good mechanical performance, intersecting joints is widely used in space steel pipe structures. However, due to the structural form, the bearing capacity of intersecting joints is mostly lower than that of the connected members, and the joints may fail before the members under the action of strong earthquakes, resulting in the failure of the whole structure. Therefore, for steel pipe structure with intersecting joints, the seismic performance of the joints is particularly important, and how to reasonably analyze the hysteretic energy performance of the joints has become a very important part of the structural design. So far, scholars from all over the world have made a lot of research results on the hysteretic properties of a variety of simple intersecting steel pipe joints, and made a breakthrough in the research results on the hysteretic properties of reinforced steel pipe joints, but there are few reports on the hysteretic properties of steel pipe joints made of high strength steel. This paper aims to review the international research results on the seismic performance of the above three types of tubular intersecting joints under low-cycle reciprocating loads, and put forward suggestions for further research of tubular joints.

2. Hysteresis Behavior of Ordinary Tubular Intersecting Joints

The early research on the hysteretic behavior of steel pipe joints can be traced back to the late 20th century. Due to the 1995 Kobe earthquake in Japan and the 1994 Northridge earthquake in Los Angeles, the weak links of steel structures were exposed. In addition to the brittle failure at the bending moment connections of steel frame beams and columns, some truss style high-rise apartment buildings also suffered serious damage. This has drawn the attention of scholars from around the world to the problems existing in steel structures, prompting people to study the performance of steel structures under earthquake action. So far, scholars from around the world have made certain research results on the hysteretic behavior of Steel pipe joints with different node shapes.

2.1 K-joints

Reference [1] conducted cyclic loading tests on 15 steel pipe truss specimens. The experimental results indicate that the bearing capacity obtained from the truss test is in good agreement with the predicted bearing capacity based on the ultimate bearing capacity formula obtained from the isolated joints test results.

Reference [2,3] conducted finite element simulations on CHS K-joints with two different welding methods based on experiments. Research has shown that the results obtained from ANSYS simulation are in good agreement with experimental results; The failure mode of non welded joints is the overall failure of the weld seam, while the hidden welded joints ultimately result in tensile cracking at the overlapped pipe weld seam; The hysteretic behavior of hidden welded joints without welded joints is better than that of un-welded joints.

2.2 T-joints

Reference [4] conducted experimental research on 12 T-joints square tube nodes under axial reciprocating loads. The experimental results indicate that within a certain range, as the diameter ratio β of the supporting pipe increases, the load-bearing capacity of joints becomes stronger and the hysteretic behavior improves; The hysteretic behavior of joints is affected by the size of the weld seam.

Reference [5] conducted axial reciprocating loading tests and finite element parameter analysis on welded T-joints of square steel pipes. Analysis shows that parameters such as the width ratio, length width ratio, and axial force ratio of the main pipe have a significant impact on the hysteresis performance of the node, with the width to thickness ratio β having the greatest effect; The existing static design formula can be used for the seismic bearing capacity design of nodes.

Reference [6] conducted experimental research on two joints with different diameter ratios of branch pipes under cyclic bending moments. The results indicate that the flexural ultimate bearing capacity of the specimens is 20% to 33% higher than the calculated value in the specifications; The ultimate bearing capacity of jionts with larger β values is significantly higher than that of joints with medium β values, and their ductility and energy dissipation capabilities are better than those of joints with medium β values..

2.3 N-joints

In reference [7] hysteretic behavior of N-joints were studied by combining test and finite element method. The results show that the local buckling in the cross area of the main branch pipe is the main energy dissipation mechanism of the joints. The local instability of the joint occurs at the place where the long branch pipe is overlapped, and then weld cracks occur, which eventually leads to the failure of the joints.

In reference [8] finite element models with different geometric parameters were established by ABAQUS, and the effects of geometric parameters β and γ on the hysteretic behavior of N-joints were compared and analyzed. The results show that with the increase of branch diameter, the effective force area of the main pipe increases and the hysteretic behavior of the joints improves. With the increase of the thickness of the main pipe, the compressive resistance of the main pipe is improved, and the plastic failure of the upper surface of the main pipe is delayed.

2.4 X-joints

In reference [9], the axial reciprocating loading test was carried out on the X-joints, and it was found that the axial tensile capacity of the joints was higher than the axial compressive capacity. reference

[10,11] studied the hysteretic behavior of X-joints bending in a plane. The results show that increasing the diametral ratio β can improve the flexural load and hysteretic behavior of X-joints. Diagoal joints have better bearing capacity and hysteretic behavior than cruciform jionts.

It is found in reference [12] that the diameter ratio β of branch head is one of the factors affecting the bending hysteretic behavior of X-joints. The resulting moment-angle curve is used as the skeleton curve, the unloading section path is introduced, and the restoring force model is adopted to establish the bending hysteretic model of X-joints outside the plane. However, this model has some defects and does not consider the influence of axial force on the hysteretic behavior of the joints. The four-spring model proposed in reference [13] solves this defect. By determining the parameter variables and introducing the restoring force criterion, a flexural hysteretic model of X-joints is constructed which can consider the influence of axial force. The applicability of the model is verified by comparison of test results and finite element analysis.

2.5 Spatial Joints

In reference [14], the static monotonic and repeated loading tests were carried out on the 4 spatial KK-joints. According to the engineering practice, a special loading device which can exert greater internal force on the bar and the joint in the test piece is designed. The results show that the joint plastic deformation will accumulate along the direction of the first plastic development, and the monotone loading curve can basically envelope the hysteresis curve.

According to reference [15], the out-of-plane flexural capacity of KK-joints is about 23% lower than that of X-joints of the same steel pipe, but the plastic development of KK-joints is more uniform than that of X-joints, and the coverage is wider. More tests are needed to verify whether the bearing capacity formula of X-joints is applicable to KK-joints.

Reference [16] studies the effects of different load forms on the hysteretic behavior of joints. The research shows that the bearing capacity of the joint is lower than that of the member, while the reverse bending joint is the opposite. Attention should be paid to the bearing capacity of the joint in seismic design.

In summary, although the research on the hysteretic behavior of ordinary steel pipe joints is increasing day by day, there are still the following problems: (1) Most of the research focuses on the hysteretic behavior of ordinary steel pipe joints under axial and reciprocating loads, and the research on the hysteretic behavior of joints under bending and reciprocating loads basically stays at X-joints, and the research on the hysteretic properties of joints under the combined action of axial forces and bending moments is even lacking; (2) It is difficult to evaluate the result normalization under the conditions of different test constraints, such as hinged and fixed at both ends of the string tube and constrained in the middle of the string tube. (3) The research on the energy dissipation mechanism of joints under low-cycle reciprocating loads is insufficient; (4) Research on the hysteresis model of intersecting nodes is scarce.

3. Hysteretic Behavior of Reinforced Tubular Intersecting Joints

In engineering, in order to improve the bearing capacity of intersecting joints, meet the design requirements of joints, and ensure the safe bearing capacity of steel pipe structures, local strengthening of joint areas is often an important means. In view of the various failure modes of pipe joints, scholars have carried out a lot of research, and the corresponding joint strengthening methods can be summarized into several forms, such as the main pipe wall thickening, the ring plate strengthening, and the inner concrete filling.

3.1 Increased Chord Thickness

Reference [17] studied the effect of increasing chord thickness on the hysteretic behavior of square tubular T-joints through experimental testing and finite element simulation. The results show that reasonable thickening of the pipe wall changes the failure mode of the joints from local buckling at the intersection of the main and branch pipes to yield failure at the reinforcement point, effectively improving the node's bearing capacity and energy dissipation capacity.

Reference [18] established a finite element model using ANSYS to analyze whether the main pipe wall should be thickened for two types of circular tubular T-joints. Research has shown that the hysteresis curve of reinforced joints is fuller and has better seismic performance than that of unreinforced joints.

3.2 Reinforced with Collar-plate

References [19,20] respectively studied the effect of ring plate reinforcement on the hysteretic behavior of circular and square tubular T-joints. The research results indicate that the reinforcement of the ring plate changes the failure mode of the joints, from the brittle fracture of the unreinforced joint to the yield failure of the reinforced joints; After the reinforcement of the ring plate, the hysteresis curve of the node is fuller and the energy dissipation capacity is stronger.

Reference [21] found through experiments and finite element studies that the L-shaped wrapped corner ring mouth plate reinforcement node is superior to the cladding and ring mouth plate reinforcement nodes, with better node bearing capacity and energy dissipation capacity.

Reference [22] studied the seismic performance of steel-concrete T-joints with void defects reinforced by ring plates. It was found that ring plate reinforcement effectively suppressed the plastic deformation of the main pipe, and the failure mode of the joint changed from tensile failure of intersecting welds to plastic failure failure on both sides of the ring plate; The use of ring mouth plates to strengthen joints with void defects can restore the original bearing capacity, ductility, and energy dissipation capacity of the joints, even better than the corresponding specimens without voids.

3.3 Fill with Concrete

Reference [23] compared the effects of internal concrete filling and pad reinforcement on the hysteretic behavior of circular tubular N-joints. Research has shown that plastic deformation occurs in the main pipe wall at the intersection of the main and branch pipes in ordinary pipe joints, while there is no significant phenomenon in reinforced joints; Concrete filled nodes have higher bearing capacity, but their ductility is relatively reduced.

Reference [24] studied the performance of circular tubular T-joints and found that the filling of concrete in the main tube effectively supported the steel tube wall, changing the failure mode of the joint. The failure mode of the specimen changed from buckling of the main tube wall to failure at the end of the branch tube and cracking of the weld seam; The filling of concrete effectively improves the ultimate bearing capacity of the node, but the hysteretic behavior of the node is reduced.

So far, although research on the hysteretic behavior of various reinforcement joints has been carried out and some achievements have been made, there are still shortcomings: (1) the types of test joints are single, and most of the specimens are T-joints, lacking experimental data support for hysteretic behavior of other types of joints, making it difficult to accurately evaluate the impact of various reinforcement methods on node hysteretic behavior; (2) The failure modes and energy consumption mechanisms of nodes under multiple reinforcement methods are different, and there is a lack of systematic induction of node energy consumption patterns; (3) There is a lack of research on hysteresis models for different reinforcement joints.

4. Hysteretic Behavior of High-strength Steel Intersecting Joints

High strength steel refers to structural steel with high strength (strength grade ≥ 460MPa), good ductility, toughness, and processability produced by microalloying and hot mechanical rolling technology [25]. In recent years, building structures have been continuously developing towards super high-rise and ultra long span directions. As the height and span of the structure continue to increase, it will inevitably lead to an increase in internal forces. The use of high-strength steel is an important means to solve the design of large internal force components. Therefore, the research on

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the seismic performance of high-strength steel is an urgent problem to be solved in the engineering field, and it is also an important issue to further improve the current relevant design specifications.

Reference [26] studied the hysteresis performance of S690 high-strength steel circular tubular T-joints under cyclic bending in the plane. The experimental results indicate that sudden fracture will not have adverse effects on high-strength steel T-joints, as the resistance of the joints has already been mobilized before fracture; On the basis of reference [27], an accurate finite element model was established, and the proposed model can accurately predict the hysteresis deformation characteristics of nodes. This model will be validated through more comprehensive parameter research.

Reference [28] studied the hysteretic behavior of high-strength steel circular tubular T-joints with five different ratios of branch pipe diameters under axial reciprocating loads. The failure mode of the node was found to be cracking of the main pipe wall near the crown at the intersection of the main and branch pipes, and the cracks extended along the cross-section of the main pipe, which is different from the failure mode of ordinary circular tubular T-joints. Research has shown that joints have good seismic performance, and the size of the main pipe section is one of the main factors affecting the hysteretic behavior of such joints.

Overall, compared with the research on the seismic performance of high-strength steel beam column joints, there is a lack of research on the seismic performance of high-strength steel joints. Specifically reflected in the following aspects: (1) Research on the performance of high-strength steel pipe joints mainly focuses on static performance, and research on the hysteresis performance of high-strength steel pipe joints under reciprocating loads has not yet begun; (2) Experimental data is scarce, and research is currently limited to T-shaped nodes, with unclear seismic performance for other nodes; (3) There is a lack of research on the energy dissipation mechanism and ductility performance of high-strength steel joints under low cycle repeated loads; (4) There is a lack of research on hysteresis models for high-strength steel joints.

5. Conclusion

Up to now, although the research on the hysteretic behavior of steel pipe joints has achieved certain results, with the increasing complexity of the structural system, the joints force form is complicated (joints withstand the joint axial force, bending moment and shear force, etc.), the current research results can not meet the domestic seismic design requirements. The following work needs to be further carried out:

(1) There are few tests on hysteretic behavior of joints under bending moments inside and outside the plane, and they mainly focus on X-joints. It is necessary to further study the hysteretic behavior of other types of joints under cyclic bending in and out of the plane.

(2) In the test and simulation of joints, there are many changes in constraint conditions, which makes it difficult to normalize the hysteretic bahvior evaluation of joints. Therefore, it is necessary to establish evaluation criteria for hysteretic behavior of joints under different constraints.

(3) The research on the hysteretic behavior of reinforced joints mainly focuses on T-joints, and it is impossible to accurately evaluate the influence of various reinforcement methods on the hysteretic behavior of joints. The hysteretic behavior of other types of joints under various reinforcement methods needs to be further studied.

(4) The research on the performance of the intersecting joints of high-strength steel joints basically remains on the mechanical performance, and it is urgent to strengthen the research on the hysteretic behavior of the joints of high-strength steel joints under cyclic axial force and cyclic bending.

(5) Research on the hysteresis model of intersecting joints is scarce, so it is urgent to propose a hysteresis model suitable for the above three types of tubular intersecting joints.

The in-depth study of a series of unsolved problems has important theoretical value and practical engineering significance for correctly grasping the hysteretic behavior of steel joints, establishing practical evaluation criteria for hysteretic behavior of joints, and improving the design method of steel pipe structures.

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