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Research and Application Status of Steel Pipe Grouting Sleeve Connection

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Abstract

Prefabricated building is one of the structural systems vigorously promoted in China, and sleeve grouting connection plays an important role in the integrity of the structure as the main connection mode between prefabricated components. In order to understand the research progress of existing scholars on the connection type of grouting sleeve, summarize the shortcomings of the current research, and analyze the research status of grouting sleeve at home and abroad in recent years through extensive research and analysis of normative standards and existing literature. The influencing factors, application status and future research directions of steel pipe grouting sleeve were introduced. The grouting of the steel pipe sleeve is connected under the axial tensile load, and the internal force is redistributed, and when the ultimate load is reached, the grouting material at all the shear keys reaches the ultimate strength. The existing technical formulas of the bonding strength of grouting sleeve connection types are not universal, and the applicability is not strong, and it is necessary to comprehensively consider the research results for further in-depth research.

Keywords

Steel Pipe Grouting Sleeve; Prefabricated Building; Shear Key; Sleeve Grouting Material.

1. Introduction

With the rapid development of the construction industry, compared with cast-in-place concrete structures, prefabricated buildings are more in line with the green and efficient requirements of building construction. As one of the technologies commonly used in prefabricated building structures, sleeve grouting connection technology is easier to operate than traditional welding and anchoring connection technologies, which is conducive to on-site construction, and is more environmentally friendly and energy-saving. The sleeve grouting connection is mainly divided into steel bar grouting sleeve and steel pipe grouting sleeve, which is divided into two kinds of setting shear key and not setting shear key, at present, the commonly used sleeve grouting connection method is to weld a certain shear key on the steel pipe and the sleeve, and pour special grouting material between the steel pipe and the sleeve and the load of the connected steel pipe is transmitted by the mechanical occlusion force between the shear key and the grouting material, and the connection bearing capacity is significantly improved due to the restraining effect of the sleeve on the grouting material. It is often used in large-scale engineering fields such as marine engineering, high-rise buildings, and bridges. In recent years, scholars at home and abroad have carried out a series of experimental studies on the grouting connection of steel pipe sleeves, which are mainly based on the bearing capacity and influencing factors of the bearing capacity of the connection, and there are more studies on the axial force of the grouting connection of steel pipe sleeves, but less on the tangential force and torsional force.

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2. The Research Process and Existing Problems of Steel Pipe Grouting Sleeve

2.1 A Brief Description of the Research Process of Foreign Grouting Sleeves

In the 70s of the 20th century, the sleeve grouting connection technology was invented by the American engineer Yu Zhanshu, and was immediately popularized and applied in Germany and Japan. The grouting sleeve was first used in offshore oil production platforms, and there was no shear key on the pipe wall, and the early British Health and Safety Executive (HSE) code and the American Petroleum Institute (API) code applied to the grouting casing without shear key.

At the end of the 70s of the 20th century, Billington et al. summarized the results of 400 full-scale and accurate scale grouting connection model tests, and proposed that the ultimate bond strength of grouting connection is affected by many parameters, including the radial stiffness of the structure, the compressive strength of the grouting material, and the shape and setting of the shear bond. The experimental study of the shear key grouting casing was carried out, and the calculation formula of the bearing capacity of the shear key grouting casing was given, and its design theory was adopted by the British Ministry of Energy. Later, 60 grouting connection specimens were designed and subjected to axial load compression tests to study the relationship between the bond strength of the specimens and the material properties and geometric parameters that affect the bond strength.

Yamasaki et al. (1980) studied the effects of pipe surface conditions and bond length on the shear bond strength of the specimens by carrying out static tests on the grouting connection models of small and large shear bonds, respectively, and studied the size effect of the shear bond strength of the specimens. It was found that the shear bond strength of large-size grouting sleeves was lower than that of small-size grouting sleeves.

Forsyth et al. (1988) studied the changes in the axial static properties of grouting joints with different height-to-shear ratios in the case of tightly arranged shear bonds, and evaluated the range of the limit values of the height-to-shear ratios of shear bonds in the HSE and API formulas through their analysis results. It is concluded that when the shear bond height ratio is about 0.075, there is a linear relationship between the grouting bond strength and the shear key height spacing ratio, and when h/s is > 0.075, the relationship between the grouting bond strength and the shear key height distance ratio is not a linear upward relationship, and the curve tends to be flat. The optimal value of the height-to-distance ratio of the shear key is between 0.07 and 0.11, and the determination of the optimal value has a great relationship with the stiffness of the steel pipe and the grouting body. In this paper, it is proposed that the HSE specification formula fully and conservatively predicts the bond strength of the shear bond when the height-to-shear ratio does not exceed 0.075, and the interpolation result of the API specification formula under the allowable f_{cu} (h/s) limit value is less than 85% of the predicted value.

Lamport et al. (1991) experimentally studied the effects of bending moment load, the position of the pile shear key relative to the casing shear key, and the eccentricity of the pile casing on the axial bearing capacity of the connection section. The data of the obtained test results were compared with the calculation results of the main specification formulas, and the safety of the specification formulas was analyzed and evaluated.

Henneberg et al. (2018) investigated the application of plain Portland cement (OPC) as an alternative filler in grouting connections, as well as the failure modes of ordinary Portland cement-filled grouting connections under underwater conditions. Compared with the high-strength grout (HPG), the ultimate bearing capacity of the ordinary Portland cement filler grouting connection test is significantly reduced, and the brittle failure process is more serious.

2.2 A Brief Description of the Research Process of Grouting Sleeve in China

At the beginning of the 21st century, Huang Liwei, Zhong Weiqiu et al. studied the grouting connection technology between pile foundation and jacket through experimental research and numerical simulation analysis. Numerical simulation method was used to conduct finite element analysis on the grouting connection between pile foundation and jacket of offshore wind power, and

ISSN: 2414-1895 DOI: 10.6919/ICJE.202404_10(4).0023

the stress situation under axial load with shear keys and without shear keys was studied. The setting of shear key can significantly improve the connection effect of grouting. By comparing the shear stress and the compressive stress and friction stress on the contact surface under the two connection modes, it is found that the setting of shear key can effectively improve the transmission ability of the connection to the axial force. The optimum range of grouting thickness and shear key size is proposed.

Zhao Yuanyuan (2009) invented a new type of grout, in which materials such as expansion agent and carbon fiber were added, and analyzed the mechanical properties of grout under different dosage. The results show that adding expansion agent and carbon fiber to grout in a certain range can improve the axial bearing capacity, energy dissipation capacity, ductility and other mechanical properties of the specimen.

In the 20s of the 21st century, Li Wei et al. designed four kinds of specimens: "shorter without shear key", "shorter with shear key", "longer with shear key" and "tapered with shear bond" for the grouting connection of large-diameter monopile foundation of offshore wind turbine. By applying axial loads to the project, it is concluded that the conical model with shear bonds has the highest axial bearing capacity, the longer model with shear bonds is relatively low, and the shorter model without shear bonds has the lowest axial bearing capacity. Therefore, it is proved that the shear key as well as the tapered shape grouting connection can help to improve the axial load-bearing performance of the connection.

Chen Haibin et al. (2016) conducted a one-way tensile test on 27 full-scale concrete-filled steel tube column grouting sleeve connection specimens to study the influencing factors of the bearing capacity and bond strength of the connecting components.

Wang Guoqing et al. (2017) carried out two sets of 30 grouting connection model specimens axial bearing performance tests to study the regular changes of the bearing performance of grouting connection specimens under different shear bond height ratio and different connection diameters. The test results show that the change of the height-to-distance ratio of the shear key greatly affects the bearing performance of the grouting connection specimen.

Wu et al. (2019) carried out axial static compression tests on 16 groups of 48 steel plate-grouting body connection specimens, and discussed the failure mode of the connecting specimens and the crack formation of the grouting material. The effects of lateral force, grouting thickness and shear bond height-to-distance ratio on the failure process and bearing capacity were studied.

To sum up, in recent years, most scholars have carried out many experimental studies on the mechanical properties, failure modes and parameter influences of grouting connections with shear keys under axial load, finite element analysis, etc., and have carried out many static load tests to determine the influence of different size parameters on the mechanical properties of the specimens.

2.3 Current Problems

At present, the experimental research on the axial mechanical properties of grouting connection mainly focuses on the model specimen composed of medium and low strength grouting material and small diameter steel pipe, especially the domestic research results, and the lack of research results and experimental data on the mechanical properties of grouting connection with high-strength grouting material in the case of large diameter, it is necessary to carry out more reliable experimental research on the grouting connection under the conditions of high strength and large diameter.

In terms of construction cost, grouting sleeve connection, as the main connection method of prefabricated buildings, has a higher construction cost than that of traditional cast-in-place building node connection. In terms of market acceptance, some users and developers are conservative and skeptical about new technologies, lacking full understanding and trust. In terms of applicability, the sleeve needs to be made in advance at the factory, and its size is mostly fixed specifications, and there are restrictions on applicability. Ensuring the firmness of the component connection is the key to the success of the prefabricated building, at this stage, most of the prefabricated building construction

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personnel in China are ordinary workers with large mobility, lack of professional prefabricated skills and knowledge, and need to be enhanced in improving professionalism.

3. Research on the Mechanical Properties of Steel Pipe Grouting Sleeve

3.1 Research on Connection Performance under Different Load Forms

In 2016, Chen Haibin et al. pulled out the grouting sleeve connection specimens of 27 full-foot concrete-filled steel tube columns through a special grouting sleeve connector for a one-way tensile test. The outer diameter of the sleeve used is 146mm, the outer diameter of the steel pipe is 102mm, and the wall thickness is 8mm. It is found that the slip failure process can be divided into four stages (cracking stage, development stage, descending stage and residual stage). It is found that with the increase of grouting strength and connection length, the shear strength of the shear surface increases, and the ultimate load value increases significantly. The strength of the grouting material increases, the bearing capacity and the bonding strength of the grouting sleeve also increase, and the connection length is directly proportional to the bearing capacity of the grouting sleeve, and the bonding strength is inversely proportional. The test results show that when the strength grade of the grouting material is low, the bearing capacity of the connecting components is low, so the strength grade of the grouting material should be selected as high strength. The estimation method of the bond strength when the connection length is different is given, when$L = 60mm$ the bond strength of the specimen can be estimated according to the formula $\tau = 0.1f_{cu} + 26$; At that time, the bond strength of the specimen can be determined by the formula $L = 80mm$ $\tau = 0.2f_{cu} + 158$ to estimate; When, the bond strength of the specimen can be estimated by the formula $L = 100mm$ $\tau = 0.13f_{cu} + 16.2$.

In 2018, Wu Liwei et al. analyzed the bond-slip constitutive relationship and the distribution law of bond stress on the contact surface through the axial tension and axial compression tests of the grouting connection of the steel pipe sleeve, and obtained: (1). When the tube sleeve grouting connection is under axial tensile and compressive load, the steel tube has a certain constraint effect, which increases the plasticity of the grouting material, and the internal force will be redistributed. Therefore, when the ultimate load is reached, the grouting material at the shear bond reaches the ultimate strength. (2) The length of the sleeve connection and the compressive strength of the grouting material are directly proportional to the ultimate bearing capacity, and under the same conditions, the bearing capacity in the tensile state is increased by 6.5% compared with the compressive state, and it is found that the load form has little influence on the bearing capacity of the steel pipe grouting sleeve connection.(3) The bond-slip full curve of the grouting connection of the steel pipe sleeve can be simplified to a 4-stage polyline constitutive model. According to the trial studies (1) For the grouting test specimen with shear key, breakage and cracks first appear at the position of shear key at the bottom of the test specimen (2) With the increase of the ratio of shear key height to distance h/s, the influence on the bearing capacity of the specimen gradually decreases, and the recommended value range of the ratio is given(0.06,0.1); (3) Within a certain range, the influence of the increase of the thickness-to-distance ratio t_g/s on the bearing capacity of the specimen is from strong to weak, and it is recommended that the selection range of thickness-to-distance ratio should be greater than 0.3 while meeting the corresponding engineering requirements.

In 2020, Wang Qiuyu et al. passed the one-way axial compression performance test and the compression-bending performance test under one-way and cyclic loads. The outer diameter of the sleeve used is 219mm, the outer diameter of the steel pipe is 168mm, and the thickness of the steel pipe and the sleeve is 8mm. The compression bending specimens are divided into 4 groups according to different axial pressures and loading methods , and the axial pressure of the specimens is $0.2N_0 \sim 0.6N_0$(which is the axial compressive bearing capacity). The test results were analyzed for compression-bending capacity, failure mode, vertical displacement, sleeve strain, hysteresis curve and skeleton curve. The results show that with the increase of axial pressure, the horizontal bearing capacity decreases by about one-third, the yield displacement angle decreases, and the ductility and energy dissipation capacity become worse, but the stiffness increases. Under the action of bending

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moment, the gap between the steel pipe and the grouting material at the close position of the two ends is easy to occur, and it is easier to be crushed under the action of contact compressive stress. $N_0 0.2N_0 0.6N_0$.

In 2020, Wang Genliang et al. carried out axial compression tests on the outer diameter of the outer pipe with the outer diameter of 580mm, 600mm, and 630mm, and the outer diameter of the inner pipe was 480mm, and the wall thickness was 12mm. The calculated results of API formulas are generally lower than the experimental results. The results show that the longitudinal and circumferential strain distribution of the steel pipe in and out of the large-diameter and high-strength grout connection model is not uniform under axial load. In a certain range, the change of the number of shear keys has the greatest influence on the mechanical properties of grouting joints, followed by the distance and size of shear keys. When the distance between shear keys, the number of shear keys, the vertical migration rate of shear keys and the ratio of diameter to thickness of grout are changed, the mechanical properties of grout connections under axial load basically increase with the increase of the height of shear keys.

3.2 Influencing Factors of Bearing Capacity

In summary, the influencing factors affecting the ultimate bearing capacity of the grouting sleeve connection of the steel pipe include the hoop stiffness of the steel pipe, the height and distance ratio of the shear key, the form of the shear key, the material properties of the grouting material, and the length-diameter ratio of the connection section.

The results show that under the same conditions, the bonding strength of the shear key in the form of round steel fillet weld is higher than that of the surfacing bead and flat bar fillet weld.

Hoopal stiffness is one of the key influencing factors affecting the connecting parts of the steel pipe grouting sleeve, under the axial tension and compression and reciprocating load, the intermediate cement slurry ring transmits the shear force of the steel pipe and the sleeve, and the ferrule effect of the steel slurry ring makes the internal cement slurry ring in a three-way stress state, and the stronger the ferrule action, the stronger the bond strength, so the stiffness of the steel pipe and the sleeve has a significant impact on the bond strength.

The shear key spacing has a great influence on the connection failure, from the perspective of force, increasing the number of shear keys makes the sleeve and grouting material more uniform, which is conducive to improving the bearing capacity, but when it is too dense, the direct shear failure along the top surface of the shear key will occur.

For grout, different water-glue ratios, glue sand ratios, mineral admixtures such as silica fume, fly ash, mineral powder, admixtures, etc. will affect its fluidity, expansion rate, material strength and other mechanical properties, and good mechanical properties can ensure that the sleeve grouting material has stable working performance.

When the aspect ratio is 2, the grouting sleeve connection section has the best performance. The eccentricity of the steel pipe and the force form of the connection section have little influence on the bond strengthf_b.

4. Application Status and Development Prospect of Steel Pipe Grouting Sleeve

At present, the concrete-filled steel tube composite structure is mainly used in high-rise buildings, wind power generation supports, offshore oil production platforms, mine supports and other buildings. Offshore wind power mainly adopts a single pile or multi-pile foundation, and a grouting casing is used to connect the pile foundation and the wind turbine tower. Because the steel pipe grouting sleeve has the same strength in all directions from the perspective of stress characteristics, and there is no low stiffness direction of rectangular section column when bearing the action of bending moment, and its torsional resistance is much stronger than that of channel steel, I-shaped steel column, etc., and the local stability of the closed section of steel tube concrete is also better than that of channel steel, I-shaped steel, etc., so the large-diameter grouting casing is not only a key node of offshore

ISSN: 2414-1895 DOI: 10.6919/ICJE.202404_10(4).0023

wind power support structure, but also used in high-rise buildings, wind power generation supports, etc. With the increasing complexity of coal mining conditions, many problems have arisen in the support process of traditional retractable supports such as bolt anchor cables. As a new type of support frame, concrete-filled steel tubular support has the characteristics of high bearing capacity, good stability, and easy welding of various accessories, so it is increasingly used in deep well soft rock roadways. Since the steel pipe grouting sleeve does not need to be welded on site, and there are certain limitations of traditional welding and mechanical connection, it is more suitable for wet places in mines where there is a risk of gas leakage.

Due to the strong support of the state for prefabricated buildings, prefabricated buildings have developed rapidly, and the application of small-diameter steel pipe grouting sleeve in the field of prefabricated concrete-filled steel tube shear wall and concrete-filled steel tube column connection has gradually increased, which can not only improve the stiffness of steel pipe and prevent steel pipe corrosion, but also improve the bearing capacity and fatigue performance of such connection methods. And the grouting sleeve connection can also be applied to various fields of mining construction engineering, including concrete-filled steel tube coal storage silo, belt conveyor support, hoist support, tank transportation support, etc. With the increasing proportion of prefabricated buildings, the development prospects of grouting sleeves are gradually increasing.

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