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Research Progress on Concrete-Filled Steel Tubes with Defects

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Abstract: Concrete-filled steel tube (CFST) structures are widely used in civil engineering due to their high load-bearing capacity and construction efficiency. However, core concrete defects such as voids and interfacial gaps significantly degrade mechanical performance, posing serious threats to structural safety. This paper systematically reviews influencing factors of CFST mechanical properties, load-bearing capacity calculation methods, and defect damage mechanisms. Studies indicate that cross-sectional shape (circular > square > polygonal), steel tube thickness, and material strength significantly affect axial compression performance. Void defects reduce load-bearing capacity by 18.5%–59% by disrupting the confinement effect, with near-wall voids causing 15%–20% greater losses than central voids. Secondary grouting and CFRP reinforcement restore 85%–92% and 10%–15% of capacity, respectively, but irreversible performance losses persist. Finite element models reveal conservative deviations (up to 20%) in current codes for thin-walled high-strength CFST columns. The study highlights higher defect sensitivity in non-circular sections, necessitating defect rate–capacity reduction coefficient tables. Future research should focus on multi-defect coupling effects, smart repair technologies, and refined computational models to enhance engineering reliability.

Keywords: Concrete-filled steel tube (CFST); Defects; Research progress.

1. Introduction

Before the pouring of traditional concrete structure, it is necessary to support the template in advance and tie the steel bar. After the concrete is condensed, the template needs to be removed, which reduces the construction efficiency. In addition, the support formwork and the binding steel pipe increase the labor cost and increase the engineering cost. In order to effectively improve the above shortcomings, a new type of component ' concrete filled steel tube ' was born. It gives full play to the material properties and achieves the effect of ' 1 + 1 > 2 '.Compared with the traditional concrete structure, its bearing capacity is higher. Its simple construction method shortens the construction period, improves the construction efficiency and saves the construction cost. Concrete-filled steel tubular structures have a history of more than 70 years in China. From 1960 to 1985, it was the stage of popularization and development of concrete-filled steel tubular columns. From 1985 to now, it is the stage of in-depth research and innovative application. The main sections of concrete-filled steel tubular columns include circular sections, square sections, and polygonal sections[2].

With the deepening of the research on the mechanical properties of concrete filled steel tube and the innovation of construction technology, concrete filled steel tube structure is widely used in high-rise and super high-rise buildings, long-span arch bridges and underground engineering[3-4].However, pouring concrete in steel tube belongs to concealed engineering, and it is impossible to directly observe the pouring quality. Such concealed engineering often makes mistakes in the construction process, which leads to the quality of core concrete cannot be guaranteed, and the overall mechanical properties of components will also be affected[5][6]. For example: a frame concrete-filled steel tubular column in Xi 'an, with internal partitions. After the pouring is completed, the ultrasonic testing of the concrete-filled steel tubular column is found to be abnormal, and the construction unit conducts openings on the spot. The results show that there is a density defect in the internal concrete[7] ;liaoning Shenyang Changqing Bridge was built in 1995.Due to many unfavorable factors such as backward construction technology and cold construction environment, the porosity of core concrete increases and the compactness decreases[8].

In summary, the internal compactness defects of concrete filled steel tube are widespread in practical engineering, resulting in a decrease in bearing capacity and a serious threat to the quality of the project. Therefore, it is of certain value to study the influence of core concrete compactness defects on the mechanical properties of concrete-filled steel tubular columns. It can comprehensively explore the mechanical properties of concrete-filled steel tubular columns with defects and provide reference for the practical application of concrete-filled steel tubular columns.

2. CFST Mechanical Performance

2.1. Influencing Factors and Finite Element Analysis

The main factors affecting the mechanical properties of concrete filled steel tube are the section shape of the specimen, the thickness of the steel tube, the strength grade of the concrete and the slenderness ratio. Most of the research focuses on circular and square concrete-filled steel tubes, and there are few studies on polygonal concrete-filled steel tubes.

Lu De-ren [9]carried out experimental analysis on the axial compression performance of concrete-filled steel tubular columns. Taking the cross-section shape (circular, square) and stirrup constraint as the changing parameters, the axial compression test of 8 concrete-filled steel tubular columns was carried out, and the stress analysis was carried out with the finite element software. The test results show that the mechanical properties of circular concrete-filled steel tubular columns and square concrete-filled steel tubular columns are basically the same. The internal stirrups not only directly constrain the core concrete, but also increase the constraint of the steel tube on the core concrete. Based on the test and simulation, the calculation formula of axial compression bearing capacity of concrete filled steel tubular columns with stirrups is proposed.

Ayough P[10] used ABAQUS finite element software to establish the axial compression model of concrete-filled steel tubular columns. Taking the cross-section form, steel grade and core concrete strength grade of the specimen as the main change parameters, the damage development process, failure mode and bearing capacity of concrete-filled steel tubular columns under different parameters were explored. The results show that the calculation accuracy of the axial compression model of concrete-filled steel tubular columns built by ABAQUS is verified. The ultimate bearing capacity of concrete filled steel tube column increases with the increase of the strength of steel tube and core concrete. The failure mode and ultimate bearing capacity of polygonal (hexagonal, octagonal) cross-section concrete-filled steel tubular columns are similar to those of square concrete-filled steel tubular columns.

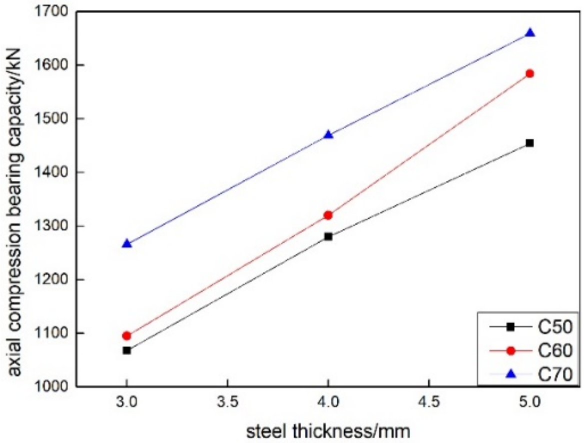

Figure 1. Axial compressive strength

Lu[11] conducted an experimental study on the axial compression performance of concrete filled steel tubular columns. The main parameters are the thickness of steel tube, the strength of concrete and the volume fraction of steel fiber. The test results show that adding steel fiber to the core concrete can effectively improve the ductility and energy dissipation of concrete filled steel tubular columns, but it has no obvious effect on the failure mode. In terms of improving ductility, the effect of adding steel fiber is the most obvious, which is more significant in high-strength concrete. Finally, the test results are compared with the finite element simulation results, and the two are basically consistent. According to the literature data, Fig.1 shows that the influence of steel tube thickness on the axial compression strength of the specimen is greater than that of concrete strength.

Le Trung[12] completed the axial compression test of stainless steel hollow concrete-filled steel tubular columns with the main parameters of concrete strength, steel tube wall thickness and section shape, and compared the calculation results of the finite element model with the test results to verify the accuracy of the model. The results show that the bearing capacity of the specimen increases with the increase of concrete strength. Increasing the wall thickness of steel tube can effectively improve the restraint ability of internal concrete.

Marcin Abramski [13]completed a total of 30 axial compression tests of concrete-filled steel tubular columns. The main parameters were cross-section form (circular, square), slenderness ratio and steel tube wall thickness. The finite element software was used to establish the concrete-filled steel tubular column model. The results show that the finite element calculation results are basically consistent with the test results, which verifies the accuracy of the model. The mechanical properties of circular concrete-filled steel tubular columns are better than those of square concrete-filled steel tubular columns. The constraint capacity of the steel tube to the core concrete increases with the increase of the wall thickness of the steel tube.

In summary, through the systematic study of the axial compression performance of concrete-filled steel tubular columns, the existing results have formed a multi-dimensional cognitive system. The test and numerical simulation show that the section shape has a significant influence on the mechanical properties. The circular section is more conducive to the hoop effect than the square section, and the polygonal section is similar to the bearing capacity characteristics of the square section. In terms of material parameters, the contribution rate of steel tube wall thickness to axial compression strength is higher than that of concrete strength, while the increase of wall thickness of stainless steel hollow steel tube can improve the restraint ability. In the reinforcement measures, the incorporation of steel fiber can improve the ductility, and the internal stirrup constraint enhances the integrity through the dual mechanism. Finite element modeling technology provides a reliable tool for theoretical analysis.

2.2. Load-Bearing Capacity Formulas

The construction of the calculation formula for the bearing capacity of concrete filled steel tube has undergone the dual evolution of theoretical exploration and practical verification. The traditional superposition method separates the calculation of steel tube and concrete, which fails to fully reflect the hoop effect and interface synergy mechanism of composite structure. However, the modern unified theory realizes the refined expression of bearing capacity calculation by establishing the constitutive relationship of composite materials. The current mainstream methods can be divided into three categories : analytical methods based on limit equilibrium theory, empirical formulas based on experimental data regression, and modified models integrated with numerical simulation. Both China 's Technical Code for Concrete Filled Steel Tubular Structures (GB50936-2014) and European Code EC4 adopt the confinement coefficient method, and the confinement effect coefficient ξ is introduced to quantitatively characterize the confinement strengthening effect of steel tube on core concrete. In recent years, more attention has been paid to the influence of multi-parameter coupling, such as considering the correction items such as void defect reduction coefficient and steel fiber enhancement factor, so that the formula gradually extends from the ideal state to the actual working condition of the project.

Ravi Kumar H [14]collected and analyzed the axial compression test data of 213 concrete filled steel tubular columns. Based on the test, the calculation formula of axial compression bearing capacity of concrete filled steel tubular columns was proposed. The calculation results are basically consistent with the test results.

In order to study the axial compression performance of high-strength concrete-filled thin-walled steel tubular columns, Lume G [15]made a total of 24 circular concrete-filled steel tubular columns with core concrete strength of 100 MPa. The four main stress modes of concrete-filled steel tubular columns, core concrete alone, steel tube without core concrete and concrete column without steel tube were used to observe the damage development process and failure mode of concrete-filled steel tubular columns under combined stress and single stress. The international standard was used to calculate the bearing capacity. Compared with the test results, it was found that the international standard was conservative.

Cai[16] carried out axial compression tests on 57 concrete-filled steel tubular short columns. The main parameters were the hoop index, the loading method and the height of the specimen. The test results show that the concrete-filled steel tubular short columns have high strength and plasticity, and the strength and deformation resistance of the concrete-filled steel tubular short columns are greatly affected by the confinement index. The calculation formula of the bearing capacity of the component is derived by the limit equilibrium method and optimized. The calculation results of the formula are basically consistent with a large number of test results, and the formula is simple and convenient for calculation.

Zhong[17] put forward the unified theory of concrete filled steel tube on the basis of superposition method and regression formula, and put forward the constitutive relation under different load forms from the direction of a new material combination. The constitutive relation reflects the working mechanism of concrete filled steel tube members. Different from the superposition method, the steel tube and concrete are separated. Finally, a new calculation method of bearing capacity is proposed, which is not only simple and effective, but also closer to the actual project than the superposition method, and effectively improves the accuracy of the calculation results.

In summary, scholars have gradually improved the calculation system through experimental data regression, limit equilibrium method optimization and unified theoretical construction. Future research needs to pay more attention to the adaptive development of multi-dimensional parameter coupling effect, new composite reinforcement technology and special-shaped section calculation theory.

3. Defect Mechanisms in CFST

3.1. Core Concrete Compaction Defects

The compactness of core concrete refers to the proportion of the volume of the solid part of the core concrete to the total volume inside the steel tube, indicating the degree of filling of the steel tube with concrete, which reflects the compactness of the concrete in the concrete filled steel tube. Common density defects in practical engineering include honeycomb surface, discrete holes, concentrated holes, void defects, debonding defects and serious delamination segregation.

The reasons for the compactness defects are as follows : (1)Structural partitions, flanges and stiffeners are often set up in concrete-filled steel tubes. The compactness of the lower concrete is reduced due to the blocking of such structures during concrete pouring. (2)The design position of concrete-filled steel tube vents is improper or it is difficult to exhaust due to blockage. Therefore, too much air inside the steel tube increases the internal pores of the core concrete, resulting in a decrease in the compactness of the core concrete.(3) Improper mix proportion of core concrete, uneven mixing or improper construction, resulting in the concrete in the concrete filled steel tubular column and the concrete at the joint is honeycomb, thus affecting the compactness of the core concrete. Under the bonding effect of cement-based material slurry, bubbles exist stably in the transition zone between cement paste and coarse aggregate, resulting in discrete hole defects in core concrete and reducing the compactness of core concrete. (4)The selection and dosage of admixtures are improper, resulting in a large number of bubbles formed inside the concrete during the preparation process. (5) The hardening shrinkage of core concrete leads to a gap between the core concrete and the steel tube wall, forming a void defect. (6) If the steel pipe wall is not derusted or the derusting is not complete, the concrete in these parts is difficult to bond with the steel pipe, which is easy to cause void.

3.2. Impact of Void Defects

The research on the mechanical influence of void defects (the formation of voids between steel tube and core concrete) in concrete-filled steel tube structure is an important topic in the field of structural engineering. The mechanism of action is mainly the failure of interface synergistic effect. The void area leads to the failure of effective constraints between steel tube and concrete, resulting in local stress concentration in the void area.

Zhang[18] found that the ultimate bearing capacity and deformation capacity of the specimens with void defects were significantly reduced compared with the specimens without defects by the axial compression test of 8 concrete-filled steel tubular columns with void defects strengthened by CFRP. CFRP reinforcement can effectively improve the ultimate bearing capacity and deformation capacity of the specimen. Compared with the one-layer CFRP reinforced specimen, the two-layer CFRP reinforcement has a greater increase in the bearing capacity and deformation capacity of the specimen.

Shao[19] completed the axial compression test of 17 concrete-filled steel tubular columns with the main parameters of void ratio and secondary grouting reinforcement. The test results show that the ultimate bearing capacity of the specimens decreases with the increase of void ratio. Compared with the specimens with defects, the bearing capacity of the secondary reinforcement specimens is significantly improved. Compared with the non-defective specimen, the bearing capacity of the secondary reinforcement specimen is slightly lower.

Han[20] carried out axial compression and eccentric compression tests on 12 concrete filled steel tubes with void defects. The main parameters are circumferential void and spherical crown void. Based on the test, a finite element model was established. The simulation results are consistent with the test results. The influence of different parameters on the ultimate strength of concrete filled steel tubular columns with void defects is revealed. Finally, the actual maximum allowable void ratio of concrete-filled steel tubular columns under eccentric load is proposed, and a simplified model of ultimate strength of concrete-filled steel tubular columns is established.

Lu[21] carried out axial compression and eccentric compression tests on concrete-filled steel tubular members with composite defects. The main parameters were void ratio and porosity. Based on the test, a finite element model was established. The model calculation results are consistent with the test results. The test results show that the bearing capacity of concrete filled steel tubular members decreases with the increase of porosity of core concrete. Reducing the void ratio and porosity of arch bridge is the key to ensure the reliability of concrete filled steel tube.

Shen[22] found that through the axial compression test of concrete-filled steel tubular columns (elliptical interface) with void defects, the void defects reduced the confinement ability of the steel tube to the core concrete, resulting in a significant reduction in the ultimate bearing capacity and initial stiffness of the specimen. With the increase of void ratio, the ultimate bearing capacity and initial stiffness of the specimen decrease significantly. Increasing the strength grade of the steel tube, the deformation ability of the specimen is enhanced.

In summary, the void defect significantly weakens the mechanical properties of concrete-filled steel tubular columns, but it can be improved by effective reinforcement measures. The ultimate bearing capacity, stiffness and ductility of the specimens decrease with the increase of the void ratio. The existing achievements have established a quantitative evaluation system for the influence of void defects, but the research on the coupling mechanism of composite defects, the development of new reinforcement technology and the adaptability of special-shaped sections still needs to be deepened.

3.3. Central Void Defects

The research on the damage mechanism of internal defects of concrete-filled steel tubular members on bearing capacity is gradually deepening. Relevant scholars have revealed the key influence of defect morphology, spatial distribution and repair process.

Hao[23] completed the axial test of 9 concrete filled steel tubular columns (including concentrated hole defects) with the defect rate and defect position as the main change parameters. The test results show that compared with the specimens without defects, the bearing capacity of the specimens with 5 % defect loss rate is reduced by 14 %, and the bearing capacity of the specimens with 20 % defect loss rate is reduced by 59 %. Under the same defect position, the ultimate bearing capacity of the specimen decreases gradually with the increase of the defect loss rate. Under the same defect loss rate, compared with the central hole defect, the bearing capacity of the near-wall hole defect specimen decreases greatly.

Zhang[24] designed the axial compression test of 27 concrete-filled steel tubular columns. The main change parameters are the hole defect rate and the defect position. The local deformation of the specimen with hole defects is more serious, and the bearing capacity is significantly reduced. Under the same defect position, with the increase of the defect rate, the bearing capacity of the specimen decreases significantly, and the time of the elastic stage is shorter. Under the same defect rate, the near-wall hole defect has a great influence on the bearing capacity of the specimen.

Wang[25] completed the axial compression test of 12 elliptical cross-section concrete-filled steel tubes with void ratio, concrete strength and steel tube strength grade as the main parameters, and established the model by finite element software. The results show that the void defect causes brittle cracking of core concrete, and the local deformation of concrete filled steel tube column is serious. The void ratio is between 0.7 % and 6.5 %, the bearing capacity of the specimen is reduced by 18.5 % ~ 34.5 %, the initial stiffness is reduced by 5.4 % ~ 17.8 %, and the ductility is reduced by 17.0 % ~ 31.4 %. The void defect weakens the restraint effect of steel tube on concrete. With the increase of strength grade of concrete and steel tube, the influence of void defect can be effectively weakened.

In summary, holes and void defects have significant regularity on the reduction of mechanical properties of concrete filled steel tubular columns. The order of defect sensitivity is : near wall defect > center defect, void defect > hole defect, elliptical section > circular section. In engineering applications, key detection and reinforcement process optimization should be implemented in defect areas. Future research should focus on the development of multi-defect coupling effect and intelligent repair technology.

4. Conclusions and Outlook

The mechanical properties of concrete-filled steel tube are significantly affected by the cross-section shape, material parameters and defect characteristics. The void and hole defects reduce the bearing capacity by 18.5 % -59 % through the synergistic effect of the failure interface, and the defect location (near the wall > center) and type (void > hole) play a decisive role in the degree of damage. In the strengthening measures, CFRP wrapping and secondary grouting can partially restore the performance, but cannot completely eliminate the influence of defects. The existing bearing capacity calculation model needs to incorporate the defect reduction factor and the material enhancement factor to improve the prediction accuracy.

Future research should focus on the following directions: (1) multi-defect coupling mechanism, such as the synergistic damage effect of void-void-shrinkage ;(2) Intelligent repair technology development, such as the whole life cycle control of self-healing concrete combined with distributed sensing ;(3)The adaptability theory of special-shaped cross-section (ellipse, polygon) is constructed, and its defect evaluation system is improved.(4) The multi-parameter bearing capacity prediction model based on machine learning breaks through the limitations of traditional formulas. Through technological innovation and theoretical improvement, the safe application of concrete-filled steel tubular structures under complex working conditions is promoted.

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