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Summary of mechanical properties of stirrup confined concrete

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Abstract: *Stirrup confined concrete members have been widely used in engineering. The excellent mechanical properties of stirrup confined concrete meet the structural safety, durability and economy. The purpose of this paper is to explore the influence 0of concrete compressive strength, stirrup yield strength, stirrup spacing, stirrup constraint form and volume stirrup ratio on the mechanical properties of stirrup confined concrete. By summarizing the development status of stirrup confined concrete at home and abroad, the constraint mechanism of stirrup confined concrete is analyzed, and the influence of concrete compressive strength, stirrup yield strength, stirrup spacing, stirrup constraint form and volume stirrup ratio on the strength and ductility of stirrup confined concrete is obtained.*

Keywords: *Stirrup confined concrete, Constraint mechanism, Mechanical properties*

1. Introduction

The research of confined concrete has a history of hundreds of years from its invention to now. From ordinary stirrup confined concrete to today 's new FRP-steel tube confined concrete, from mechanical properties to constitutive relations, the research results have common constraint constitutive relation models, constraint theories and research ideas. Studying the constraint effect of confined concrete can better exert the constraint effect of different constraint forms on concrete and facilitate engineering design by dividing different constraint levels. The reasonable use of the constraint effect can reduce the engineering cost and achieve economic benefits. Based on the research of domestic and foreign scholars on reinforced concrete columns, this paper summarizes the mechanical properties of confined concrete, which can provide the basis for the qualitative research and analysis of the mechanical properties of stirrup confined concrete columns.

2. Research status of stirrup confined concrete at home and abroad

2.1. Foreign research present situation

In 1971, Kent and Park [1] proposed a stress-strain model of concrete confined by rectangular stirrups based on previous studies. The model consists of a parabolic ascent section, a straight-line descent section and a horizontal section. The effects of stirrup ratio, section size, stirrup spacing and concrete strength are considered. It is considered that the rectangular stirrup constraint can increase the deformation capacity of the core concrete after reaching the peak compressive stress. This model has been widely cited by later researchers. However, the influence of stirrup form on the strength and deformation capacity of concrete is not considered in the research process.

In 1988, Mander et al.[2] carried out axial compression tests on 31 full-scale stirrup confined concrete columns. Considering the stirrup form, stirrup strength and concrete strength, a constitutive relation model suitable for different stirrup forms (including circular stirrups, spiral stirrups, rectangular stirrups, octagonal composite stirrups, etc.) was proposed. Aiming at 307MPa ~ 340MPa stirrups, this paper defines the strain at the initial fracture of stirrups as the ultimate compressive strain, and establishes the ultimate compressive strain formula of confined concrete according to the energy principle. The model is based on confined ordinary strength concrete, and its adaptability to high strength and ultra-high strength concrete needs further study.

In 2001, Li Bing et al.[3] artificially studied the stress-strain properties of high-strength concrete confined by ultra-high strength and ordinary strength stirrups, and conducted axial compression tests on

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40 high-strength concrete columns confined by full-size high-strength stirrups. The strength of concrete is 35.2MPa-82.5MPa, and the yield strength of stirrups is 430MPa and 1300MPa. The effects of stirrup spacing, stirrup ratio, stirrup diameter and longitudinal reinforcement distribution are also considered. Through the analysis of the experimental data, Li Bing et al. proposed a stress-strain constitutive model suitable for ordinary stirrups and high-strength stirrups confined high-strength concrete circular and rectangular columns. In this model, the parameter β of each test curve is obtained by the test method and the error method, and the regularity is poor, which needs to be improved. Moreover, the article does not involve the study of ultra-high strength concrete, and the scope of application is limited.

In 2018, Shanaka et al. [4] conducted axial compression tests on confined ultra-high strength concrete columns with concrete strength ranging from 100 MPa to 150 MPa, volume stirrup ratio from 0.8 % to 2.1 %, and stirrup yield strength of 360 MPa. Combined with the test results, the author established an analysis model to predict the stress-strain relationship of ultra-high strength concrete, which is used to predict the stress-strain relationship of confined concrete columns with concrete strength of 100MPa - 160MPa. The model studies the constitutive relationship of stirrup confined ultra-high strength concrete, and has high accuracy in predicting the stress-strain relationship of stirrup confined ultra-high strength concrete. However, the strength of stirrups used in the test is low, and the influence of longitudinal reinforcement ratio and longitudinal reinforcement distribution on the strength and deformation capacity of confined concrete is not considered.

2.2. Domestic research status

In 1980, Lin Dayan [5]of Tsinghua University proposed the full curve equation after studying the stress-strain performance of concrete under square hoop constraint. After research, he concluded that the rectangular stirrups had little effect on the bearing capacity of the members with ordinary stirrup ratio, but the deformation capacity of the specimens was greatly improved.

In 1981, Guo Zhenhai and Zhang Xiuqin[6] of Tsinghua University made 86 plain concrete prism specimens for experimental research. In this paper, the effects of loading rate and concrete strength on the deformation, crack and strength of concrete are studied. The relationship between the shape of the stress-strain curve and the failure mode is discussed, and the necessary parameters of the whole curve are given. In 1985, Zhang Xiuqin, Guo Zhenhai et al.[7] studied the stress-strain curve of confined concrete on the basis of studying plain concrete, and proposed the corresponding full curve equation. The model is clear, and the rising and falling sections depend on two independent test parameters and. These two parameters are related to the characteristic value of the hoop, which are obtained by the least square method and need to be determined by looking up the table. However, the concrete strength grade of the test specimens is between 28 MPa and 40 MPa, and the adaptability to high-strength and ultra-high-strength concrete needs to be verified. The test only considered the change of stress-strain curve of confined concrete with rectangular stirrups, and did not consider the influence of other stirrup forms on the bearing capacity and deformation capacity of confined concrete.

In 1994, Ye Lieping and Ye Yanhua[8] carried out a comparative test of two sets of stirrup confined high strength concrete under axial compression, and obtained the corresponding stress-strain curve. The volume stirrup ratio in the test ranged from 0.135 % to 1.621 %. The test results show that the existence of stirrups can significantly improve the ductility of the structure, and the form of stirrups has a certain degree of influence on the stress-strain curve of concrete. In addition, it is found that when the ratio of stirrup spacing to constrained section width is greater than or equal to 2.5, stirrups will not play a role.

In 1997, Guan Ping, Wang Qingxiang and other scholars[9] studied the uniaxial compression test of high strength concrete rectangular specimens confined by grid composite stirrups. The rising section of the stress-strain curve is expressed as a polynomial, and the falling section is expressed by a rational equation. Among them, the parameters of the descending section are related to the volume stirrup ratio, stirrup size and spacing, stirrup strength and concrete strength. The test results show that the grid composite stirrups can improve the mechanical properties of confined high-strength concrete specimens. Under the same other conditions, the smaller the stirrup spacing and the larger the volume stirrup ratio, the greater the peak compressive stress and the corresponding peak compressive strain of the confined concrete column.

From 2009 to 2014, Shi Qingxuan [10][11] studied the stress-strain constitutive relationship of high strength concrete confined by high strength stirrups. Among them, the yield strength of stirrups is 411 MPa, 716 MPa and 1120 MPa respectively, and the concrete strength grade is C70-C80. According to the test results, a calculation method for the stress of the corresponding high-strength stirrups when the

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confined concrete reaches the peak compressive stress is proposed, and the stress-strain curve equation of the confined high-strength concrete is established. In the calculation formula of stirrup stress corresponding to the peak compressive stress and ultimate strain of confined concrete given by Shi Qingxuan et al.[12][13], the influencing factors such as stirrup strength, concrete strength and stirrup spacing are considered. The stirrup may not yield when the confined concrete reaches the peak compressive stress and ultimate strain. If the stirrup yield strength is put into the empirical formula as an independent variable, there is a certain error in the calculation of stirrup stress[14].

3. Restraint mechanism of stirrup confined concrete

The constraint forms of concrete can be divided into active constraint and passive constraint. As a copper cylinder filled with sand, a vertical force is applied to the sand, so the constraint stress of the copper cylinder to the sand is the active constraint, and the whole sand does not undergo axial deformation during the constraint process; passive constraint means that the constraint stress of concrete changes with the increase of axial deformation, such as stirrups, steel tube confined concrete and carbon fiber confined concrete. With the increase of axial deformation, the lateral deformation increases, resulting in the increase of constraint stress.

Under the action of axial pressure, the concrete member produces transverse deformation. With the development of micro cracks in the concrete, the volume of the member expands and the stirrup bends. The reaction force of the stirrup on the concrete in the core area makes the member in a three-dimensional compression state, which delays the development of cracks in the concrete, thereby improving the bearing capacity and ductility of the member. Stirrup-constrained components are passive constrained components. When the axial stress of the component is less than the peak stress of the same plain concrete component, the lateral deformation of the concrete is very small, and the confinement effect of the stirrup is not obvious. Due to the existence of stirrups, the connection between the concrete in the core area and the concrete in the protective layer is weakened. As the stress continues to increase, the concrete in the protective layer gradually falls off, and the force it bears is transferred to the concrete in the core area, which further increases the lateral deformation of the concrete in the core area.

For the rectangular stirrup section, the binding of stirrups and longitudinal reinforcement is constrained by the tensile stiffness of the steel bar. The constraint effect is better, and the binding force of the concrete is larger. The horizontal section of each limb of the stirrup is constrained by the bending stiffness, and the constraint effect is poor, and the constraint force on the concrete is small. This is the ' arch effect ' caused by the rectangular stirrup on the concrete binding force along the perimeter of the stirrup distribution is not uniform[15]. Sheikh[16] proposed effective confinement region and non-effective confinement region in the study of confined concrete, which makes it convenient to calculate the confinement stress of stirrup confined concrete.

4. Influencing factors of mechanical properties of stirrup confined concrete

The influencing factors of stirrup confined concrete are the main factors of concrete strength, stirrup yield strength, stirrup spacing, stirrup constraint form, volume reinforcement ratio, secondary factors of longitudinal reinforcement ratio, size effect, stirrup structure and so on. According to the previous research status at home and abroad and the constraint mechanism of stirrup confined concrete, the five main influencing factors of concrete strength, stirrup yield strength, stirrup spacing, stirrup constraint form and volume reinforcement ratio are summarized.

4.1. Compressive strength of concrete

Concrete strength is an important factor affecting the bearing capacity of confined concrete columns. The research shows that under the same conditions, the higher the concrete strength grade, the greater the ultimate bearing capacity of confined concrete columns. However, the higher the strength of concrete, the more significant the brittleness. The brittleness of the material will affect the ductility of the structure, especially the ductility of the compression members used to exert the compressive properties of high-strength concrete. The test results of Cusson and Paultre[17] both show that the ductility deformation capacity of the column decreases with the increase of the compressive strength of the concrete. Therefore, the compressive strength of concrete cannot be continuously enhanced, and the mechanical properties of confined concrete need to be enhanced through multiple factors.

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4.2. Stirrup yield strength

The stirrups provide effective constraint stress to the core concrete, which improves the strength and ductility of the core concrete, and the yield strength of the stirrups determines the upper limit of the effective constraint stress. Therefore, the use of high-strength stirrups can improve the effective constraint of the core concrete and enhance the ability of the longitudinal reinforcement to resist buckling, thereby increasing the ductility deformation capacity of high-strength concrete columns. Legeron F [18] conducted a comparative test of four groups of high-strength concrete columns with different stirrup yield strengths and the same remaining conditions. The stirrup constraints in each group are different. The test results show that increasing the strength of stirrups can effectively improve the ductility of high-strength concrete columns. At the same time, it should be noted that when the volume stirrup ratio is very small, only increasing the yield strength of the stirrup has little effect on the strength and ductility of the column, which can be ignored. Only when a sufficient amount of stirrups are configured, increasing the yield strength of stirrups will greatly improve the strength and ductility of high-strength concrete columns. However, with the research of scholars, it is found that high-strength stirrups do not yield in the axial compression experiment of stirrup-confined concrete columns, and a lot of research on high-strength stirrups is needed.

4.3. Stirrup spacing

A large number of experiments have proved that when the volume stirrup ratio is the same, the descending curve of the member with smaller stirrup spacing is more gentle and the ductility is higher. This is because the stiffness of the stirrup between the constrained longitudinal reinforcements decreases rapidly with the increase of the spacing of the longitudinal reinforcements. In the constraint plane, the constraint effect mainly depends on the spacing of the constrained longitudinal reinforcements. Outside the constraint plane, the constraint effect is mainly controlled by the spacing of the stirrups. Therefore, the use of stirrups with smaller diameter and dense spacing can improve the constraint effect of the member without changing the volume stirrup ratio. It has been proved by experiments that when the stirrup spacing is greater than 1 - 1.5 times the cross-section width of the component, the performance of the constrained component is not much different from that of the unconstrained component [19]. From the calculation formula of the effective constraint stress f_{le}, it can also be seen that when the stirrup spacing is greater than 2 times the width of the section, the effective constraint coefficient f_{le} will be negative, which means that the stirrup will lose the constraint effect.

4.4. Restraint form of stirrups

The common forms of stirrups are rectangular stirrups, diamond composite stirrups, well-shaped stirrups, cross stirrups, circular stirrups and spiral stirrups. Different stirrup forms have different restraint effects on core concrete columns. The constraint effect of composite spiral stirrups is better than that of simple ring stirrups, which can effectively improve the strength and ductility of concrete columns. The simple form of stirrups contains only one core area, while the complex form of composite stirrups can divide the core concrete into more core areas, and this division can improve the constraint effect of the core concrete. Studies have shown that circular stirrups and bolted stirrups make the column subject to a more uniform constraint, and the constraint effect is higher than that of other shapes of stirrups[20].

4.5. Stirrup stirrup ratio

The volume stirrup ratio is related to the size of the core concrete, the spacing of the stirrups and the cross-sectional area of the stirrups. The larger the volume stirrup ratio, the more the corresponding stirrups, the greater the restraint effect on the core concrete, and the higher the strength and ductility of the confined concrete.

5. Conclusion

Through the comparison of the current situation at home and abroad, the working mechanism of stirrup confined concrete is analyzed, and the rules of various influencing factors are summarized. The following conclusions are obtained: (1) The compressive strength of concrete has a great improvement on the strength and ductility of stirrup confined concrete. However, with the increase of concrete strength,

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the brittleness of concrete is also increasing. It is necessary to reasonably configure stirrups to limit the brittleness of high-strength concrete. The constraint effect of circular stirrups is better than that of rectangular stirrups. (2) Composite stirrups that divide the core concrete into multiple core areas should be selected. (3) Increasing the stirrup yield strength, volume stirrup ratio and spacing can directly improve the strength and ductility of confined concrete. Studying the influence of various factors on stirrup confined concrete is helpful to the actual use of the project, and to establish the stress-strain constitutive relationship of stirrup confined concrete, and to improve the theory of stirrup confined concrete.

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