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Summary of Research on Shear Strength of Keyed Joints in Segmental Precast Assembled Bridge

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Shear keys are important parts that affect the mechanical properties and durability of segmental precast concrete bridge structures. In order to improve the understanding of the mechanical properties of the shear key of the segmental precast bridge, this paper summarizes the factors affecting the shear performance of the key teeth joints of the segmental precast bridge according to the relevant research at home and abroad, including the area of the shear key, the number of key teeth, the height of the key teeth, the form and the layout scheme. This paper expounds on the research results of the mechanical properties of the key teeth joints at home and abroad, including the failure mode and crack development law of the key teeth test, the theoretical derivation of the shear bearing capacity formula and the analysis of the finite element simulation results.

Keywords: Shear bonds; segmental precast; concrete bridges; dry joints; glue joints.

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1. INTRODUCTION

The segmental prefabrication method of the bridge was first developed in France, and the bridge construction engineer Eugen Freyssinet first used this technology to build the Luzancy Bridge on the Man River in France [1,2]. Developed countries such as Europe, the United States and Japan have studied the construction method of segmental prefabrication earlier, such as the Shelton Bridge with dry joints in New York State in 1952; in 1962, the Choisy-Le-Roi bridge with glued joints was used on the banks of the Seine in southern Paris [3]. In this regard, some Western countries have accumulated rich research and construction experience and put forward and formed corresponding norms and suggestions to guide the design and construction of such building structures in Western countries. China's research on this aspect started relatively late and has not yet formed a mature system of norms and standards.

Unlike the integral casting bridge, the connection between segments is the weak part of the segmental precast assembled bridge. Even if multiple shear keys and epoxy resin adhesive joints are used, the mechanical performance or durability of the connection may be caused by the quality defect of the key block or the unstressed steel bar in the key block. The shape, size, number and distribution position of shear keys affects the overall force of the bridge. In recent years, with the promotion of the application of segmental precast bridges, bridge scholars at home and abroad have carried out a series of studies on shear connectors. Through shear failure experiments and numerical simulation, the influence of shear connector size, number and arrangement on shear connectors is analyzed.

Based on the scientific research results and engineering experience at home and abroad, this paper summarizes the research progress of the mechanism of shear keys on the mechanical properties of concrete bridge finishing.

2. SEGMENTAL JOINT FORM

In the construction practice of segmental precast concrete bridges, there are three main types of segmental joints: dry joints, wet joints and glue joints.

The dry joints do not use any treatment methods or bonding materials, and the segments are directly assembled. The advantages are simple construction technology and fast construction speed. The disadvantage is that the steel bars lack protection, and the steel bars at the joints are easy to corrode, resulting in a decrease in the shear performance of the structure [4]. Wet joints will add fillers at the joints, and the filling materials are generally concrete or cement mortar. The advantage is that the steel bar at the joint can be basically protected, and the error of the assembly at both ends of the segment can be corrected. The disadvantage is that the binding capacity of new and old concrete after pouring is insufficient, affecting the project's quality, and the concrete pouring and maintenance at the joints prolong the construction period. Structural adhesives such as epoxy resin glue are generally used to bond the two ends of the segment. The advantage is that the epoxy resin adhesive has good performance, which can significantly improve the joints' performance and enhance the overall structure's safety and durability [5,6]. The disadvantage is that the cost of epoxy resin adhesive is expensive.

3. RESEARCH ON DRY JOINT

3.1 Dry Joint Specimen Experiment

In 2005, T. Wakasa [7] studied the shear strength of precast beams and found that it is sometimes too conservative to consider any shear keys, while it is too optimistic to consider all shear keys. Under the same conditions, the shear key can increase the shear strength of concrete beams by more than 35 %. Due to the large opening of the segment, the shear efficiency of the upper key teeth is not high, so only the effect of the shear key located in the compression area of the segment joint section on the shear capacity of the segment beam is considered in the shear strength calculation. Based on this, the shear strength calculation formula of the segment precast beam is proposed, and the following measures can be used to enhance the shear capacity of the beam : increasing the prestress of the upper part of the segment section, increasing the height of the bottom compression zone, reducing the opening width of the segment and using both the external shear key and the internal shear key.

In 2007, Li Guoping [8] studied the influence of the type, number and position of the joints on the shear performance of the beam by the experiment of the shear performance of the segmental external prestressed concrete beam.

Experiments show that when the beam is close to failure, the crack width at the glued joint position exceeds 10 mm, and the crack width at the dry joint position exceeds 40 mm due to the absence of prestressed tendons. The number of joints has no effect on the shear capacity of the structure and the formation of cracks, but the distance between joints and loading points has a significant effect on the shear capacity and crack morphology of concrete.

In 2014, Haibo Jiang [9] studied the shear strength of dry joints with keyways in segmental precast concrete bridges. Under different confining pressure stress levels, the number, length and distance between keys were set as key parameters. The shear performance, shear bearing capacity and crack morphology of key teeth in flat joints, integral joints and steel fiber joints were tested. Two crack modes of a single key are given in the test, which shows the continuous failure phenomenon of multi-key dry key teeth from the bottom key to the top key and is verified by finite element simulation. Based on this, the shear failure mechanism of continuous failure of multi-key dry joints is proposed, and the difference between the test results and the adopted formula is explained. It is suggested that the shear strength reduction coefficient of three-key dry joints is 0.7. In addition, the experimental results show that steel fiber has a significant effect on the shear strength of single bond dry joints. The shear strength of the key teeth is proportional to the normal stress and the height of the key teeth. The three-key dry joint has stronger shear strength than the single-key dry joint and the double-key dry joint. However, due to the non-uniformity of the shear key force, the overall bearing capacity of the beam is not proportional to the number of key teeth.

In 2016, Wang Jingquan [10] considered the influence of bending moment on the mechanical properties of the key teeth at the joint and analyzed the limit state. Based on the calculation method of the Mohr circle, the calculation formula of shear capacity at the joint was obtained. Compared with the AASHTO calculation formula, the calculation is conservative when considering the influence of the bending moment. The calculation results are smaller than the experimental values of single key tooth dry joint and single key tooth and multi-key adhesive joint and are more consistent with the experimental values of multi-key tooth dry joint.

In 2019, Shen Yin [11] obtained the non-uniform coefficient of shear stress distribution of key teeth according to the stress distribution law of shear keys on segmental precast assembled concrete bridges. The reason for the non-uniform stress of shear key teeth is explained theoretically, and the shear bearing capacity calculation formula considering the non-uniform coefficient of shear stress distribution is obtained. The research results show that the non-uniform degree of shear stress distribution will increase with the increase of the number of shear keys, and when there are more shear keys on one side, the peak value of shear stress will move to the other side.

3.2 Finite Element Simulation of Dry Joint Specimen

In 2006, J. Turmoa [12] studied the finite element analysis method of externally prestressed segmental concrete structures, which was verified by the shear test of 7m long segmental beams, and three models with different complexity were proposed. The first method attempts to reproduce the behaviour of the beam by modelling the joints with their true geometric dimensions. The second model improves the previous model by introducing cracks observed in discrete crack simulation experiments. The third model evaluates the possibility of using a simplified flat joint model to reproduce the experimental test results without considering the geometric properties of the key interlock. This study is mainly to clarify the shear flow mechanism in this type of structure and analyze the stress flow formed in the web of these types of structures after the joint is opened.

In 2011, Zou Linbin, Jiang Haibo et al. [13] based on the actual project, using the finite element analysis software for nonlinear numerical simulation, analysis of segmental precast construction of external prestressed concrete bridge dry joint direct shear mode stress mechanism, the following conclusions: under the same load, the displacement of each shear key in the joint increases gradually from bottom to top; however, the stress distribution of the shear key teeth on the joint section is larger at the top and bottom of the section, and the rest is smaller; under the same load, the ratio of vertical pressure to load on the vertical bearing inclined section of the key teeth is a fixed value, the bearing shear force of the key teeth is small, and the proportion of friction is large.

In 2014, Qiu Yun [14] studied the shear performance of the key teeth of the dry joint of the externally prestressed segmental precast bridge. The key teeth of the component are plain concrete, and three different initial normal stresses are applied to the root of the key teeth, 1 MPa, 1.5 MPa and 2 MPa, respectively. At the same time, the finite element analysis software is used to simulate the experiment to study the influence of the size of the key teeth on the strength of the shear key teeth in the dry joint of the bridge. The results show that the reinforcement near the root of the shear key teeth can effectively control the development of cracks and improve the shear capacity of the shear key. The AASHTO formula underestimates the shear capacity of the single key tooth dry joint under this reinforcement method. The shear capacity of the single key shear key in dry joints increases slightly with the increase of normal stress. Comparing the model test with the numerical simulation results, the ultimate shear load values of the two are in good agreement, and the crack development of the shear key teeth is also consistent.

In 2020, based on the actual engineering project, Cao Songbai [15] studied the shear keys at different positions of the segmental precast assembled box girder and the difference in the mechanical performance of the shear keys caused by the number of different shear keys. From the force point of view, the shear keys on the roof, wing plate and web are the main shear keys, and the shear keys on the bottom plate have smaller shear stress. In the design, the shear keys on the roof, wing plate and web of the segmental beam should be strengthened. In order to ensure the shear uniformity of each shear key and reduce the shear stress level of each shear key, the shear key of the web can be strengthened by the arrangement of multiple key teeth.

In addition, Shaarbafal and Jianghb [16,17] studied the dry joint specimens. The results show that the shear keys on the upper part of the joint are mainly stressed when the key teeth are stressed, and the shear keys on the bottom plate only bear a small part. This conclusion can provide a reference for optimizing the design of key teeth on joints and improving the overall bearing capacity of joints.

4. STUDY ON ADHESIVE JOINT

4.1 Finite Element Simulation of Dry Joint Specimen

In 2007, Wang Shuangyan [18] carried out the shear performance test of segmental externally prestressed concrete beams. The research shows that the shear capacity of the test beam glue joint section and the formation of cracks are not necessarily related to the number of beam joints. However, the distance between the beam joint and the loading point directly affects the shear capacity of the test beam and has a very important influence on the crack morphology.

In 2014, Yuan [19] studied the mechanical properties of the bonded joints of segmental external prestressed concrete bridges under direct shear and studied the influence of shear key tooth depth and pitch on the overall shear performance of the bridge. Through the test, the vertical displacement law and failure load of the shear key after loading are obtained. The specimen will reach the ultimate failure load soon after cracking, and there is no obvious yield stage. The direct shear bearing capacity of the shear key of the adhesive joint is directly proportional to the direct shear failure area, positively correlated with the depth of the key teeth, and has no obvious relationship with the setting of the pitch. In the design, the spacing of the shear key teeth can be increased to reduce the construction difficulty of applying epoxy resin adhesive.

In 2015, Li Xuebin [20] designed axial tensile adhesive specimens. Under various loading conditions, the ultimate tensile strength of the adhesive joints of segmental precast assembled bridges was obtained. The treatment results of the joint concrete surface have a significant effect on the bond strength between epoxy resin adhesive and concrete. The ultimate tensile strength between epoxy resin adhesive and concrete can reach 3MPa.

In 2019, Le [21,22] et al.proposed the prestressing scheme of unbonded CFRP tendons in precast segmental concrete beams, which reduced the second-order effect of external tendons compared with the external prestressing scheme. At the same time, CFRP tendons have good corrosion resistance, no need for beam grouting, and convenient construction; the test results show that the flexural capacity of segmental beams with unbonded CFRP tendons is about 71% of that of segmental beams with bonded tendons, and the structural ductility is 7 times that of segmental beams with bonded tendons.

In 2019, He Jiale [23] studied the shear performance of high-speed railway segmental prefabricated cemented joint-assembled bridges. The test results show that the failure of the specimen is a brittle failure, and the existence of epoxy resin glue increases the integrity of the beam and improves the shear capacity.

In 2019, Ghafur H. Ahmed [24] proved that the application of epoxy resin glue could minimize the defects of key teeth, make the shear stress distribution on the joint surface more uniform, and reduce the uneven level of shear stress through the direct shear test of segmental precast assembled glued box girder bridge.

In 2022, Xu Xiaochen [25] 's research shows that due to the particularity of epoxy resin adhesive materials, the construction operation should be streamlined and standardized. In preparation before construction, special attention should be paid to the adverse effects of epoxy resin adhesive on operators to avoid construction safety accidents. In construction, attention should be paid to the thickness and curing time of epoxy resin adhesive, so as to improve the construction quality.

In 2023, Gou Wenzhong [26] conducted a full-scale experimental study on the shear key of the adhesive joint. The results show that when the thickness of the epoxy resin adhesive is 1mm, 3mm and 8mm, the shear-bearing capacity of the specimen is positively correlated with the thickness of the epoxy resin adhesive. The shear bearing capacity and plastic deformation capacity of the double bond specimen are better than those of the single specimen.

In 2010, Li Jiading [27] introduced the empirical formula on the basis of the bearing capacity formula of the key tooth joint of AASHTO, and obtained a new formula for calculating the direct shear bearing capacity of the joint. According to the equilibrium principle in the limit state, the calculation formula of shear capacity of joints under bending-shear failure mode is derived.

In 2018, Cai Zheng [28] carried out a push-out test study on the bonded shear key, demonstrated the failure process and failure mode of the bonded shear key, and found that the failure of the specimen did not occur in the bonding layer. The shear performance of the bonded shear key was studied by the load-slip curve and the ultimate shear capacity. The spring element was used to simulate the epoxy resin bonding layer for finite element analysis. The simulation analysis results were compared with the experimental data, and the influence formula of the bonding thickness on the shear capacity of the bonded shear key was fitted.

In 2020, Hu Hao [29] proposed the concept of moment-shear bearing capacity curve at the joint of segmental precast assembled beams and proposed a unified analysis method for joint bearing capacity.

In 2020, Pan [30] considered the influence of different number of key teeth on shear performance, and changed the correction coefficient of key teeth to 1.1, and the calculated value was closer to the experimental value of single-tooth and three-key-tooth adhesive joints.

4.2 Finite Element Simulation Study of Adhesive Joint Shear Key

In 2017, Wang Wenjing [31] established the finite element model of a continuous beam bridge based on the actual project, studied the stress state of segmental precast assembled beam bridge under different working conditions and calculated the bearing capacity. Considering the overall performance of the continuous beam bridge, the influence of the adhesive joint on the performance of the continuous beam bridge is neglected when the finite element model is established. The following conclusions are obtained: There are joints between the segments of the continuous beam bridge, and the joints break the longitudinal non-prestressed steel bars, so the bending stiffness of the main beam is reduced. In the limit state design, the bending stiffness and shear strength can be reduced, or the internal prestressing tendons in the precast segmental box girder can be increased so as to improve the bearing capacity of the section and strengthen the integrity of the structure.

In 2018, Zhang Tianbao [32] conducted a local analysis of the epoxy resin adhesive joint shear key through the finite element software and found that the thickness of the epoxy resin adhesive was positively correlated with the main tensile stress at the joint and the unevenness of the stress distribution. Because the elastic modulus of epoxy resin glue is much smaller than that of concrete, too thick glue will reduce the overall stiffness of the beam.

In 2021, Zheng Fan [33] numerically simulated the stress of the key teeth of the adhesive joint by finite element software. The simulation results show that increasing the inclination angle of the key teeth can improve the shear resistance of the key teeth. It is suggested that the design of 45 ° inclination angle should be adopted in the joint design.

5. CONCLUSION

This paper introduces the experimental, theoretical derivation and finite element analysis-related research on the mechanical properties of shear connectors of segmental precast assembled bridges at home and abroad, and summarizes the research results of shear connector failure modes, shear bearing capacity and shear bearing capacity calculation methods. The main conclusions are as follows:

(1) The theoretical derivation of scholars at home and abroad proves that the shear stress distribution in multi-key-tooth specimens is not uniform, which leads to the conservative calculation of the bearing capacity of joint specimens. The research on the shear capacity of dry joint specimens has been relatively perfect. At present, the research direction of scholars is mostly to carry out experiments to partially correct the existing formulas.

(2) The test results of many scholars show that the influence factors of the joint bearing capacity of the precast segmental beam are complex, and the shear strength of the key teeth is proportional to the normal stress and the height of the key teeth. 3 key teeth have higher shear strength than single and double key teeth. However, due to the non-uniformity of the shear key force, the overall bearing capacity of the beam is not proportional to the number of key teeth. Some scholars have carried out finite element simulations on the key joint specimens by setting up different research parameters or modelling methods to obtain the stress state of the key teeth. When the key teeth are stressed, the shear key on the upper part of the joint is the main stress part, and the shear key on the bottom plate only bears a small part of the shear force. The finite element simulation results can provide some reference for the design of the key teeth on the joint and the optimization of the bearing capacity of the joint.

(3) It can be seen from the research results of scholars that the application of epoxy resin glue on the joint surface can effectively improve the bearing capacity of the beam, but the specimen will reach the failure state without an obvious yield stage after cracking, which belongs to brittle failure. The failure of concrete at a certain distance from the joint is not considered in the test of the adhesive joint specimen, and whether it is the failure of plain concrete needs to be verified.

(4) Scholars have conducted experimental research or theoretical research or finite element simulation on the adhesive joint shear key or the specimen or bridge coated with epoxy resin. The results basically reflect that the discontinuity of the steel bar at the joint leads to the reduction of the overall stiffness of the structure. The thickness of the epoxy resin has a significant effect on the bearing capacity. Therefore, the epoxy resin should be applied evenly and the thickness should be controlled as much as possible in the construction.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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