Research Review on Mechanical Properties of Segmental Assembled Bridge Joints

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Abstract. The use of segmental assembled bridges offers significant benefits in terms of construction efficiency and convenience. Nonetheless, it is crucial to address the issue of lower mechanical properties such as the stiffness, strength, and ductility in the joints when compared to the adjacent sections. This has become a key focus of research within the realm of segmental assembled bridges. In this regard, this paper provides a comprehensive overview of the current research on shear performance, seismic performance, and calculation methods for shear bearing capacity pertaining to segmental bridge joints, both domestically and internationally. Additionally, by critically analyzing the failure modes and characteristics observed in segmental bridge joints subjected to extreme conditions, including shear bearing capacity and seismic forces, this study highlights the existing design flaws and shortcomings in segmental bridge design, anticipating that the findings of this research will serve as a valuable insight for subsequent investigations in the field.

Keywords: segmental assembled bridges · joints · shear performance · seismic performance · calculation formula of bearing capacity

1 Introduction

The advantages offered by precast segmental assembled concrete bridges in terms of fast construction progress, high construction quality, space-saving attributes, and reduced environmental impact make them indispensable in urban bridges, sea-crossing bridges, and emergency replacement and emergency repair of damaged bridges. Statistical data attests that segmental precast technology has emerged as a dominant approach in the design and construction of prestressed concrete bridges across the United States, with over 50% of such bridges employing this innovative method [1]. Differing from ordinary bridge structures, since the presence of non-prestressed reinforcement exhibit discontinuity at these junctions, the unique characteristics of precast segmental bridges necessitate meticulous considerations for the joints between segments due to the inherent reduction

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in stiffness, strength, and ductility in comparison with adjacent sections during both the design and construction stages. Scholars at home and abroad have carried out extensive and in-depth research work on the mechanical properties of segmental assembled bridge joints, mainly focusing on three aspects: shear performance, seismic performance, and calculation method for shear bearing capacity of segmental assembled bridge joints.

2 Current Status of Research on the Shear Performance of Segmental Assembled Bridge Joints

Comprehensive and profound research has been conducted by scholars both domestically and internationally on the mechanical properties of adhesive joints in segmental assembled bridges. Research primarily revolves around investigating the influence of prestress layout on the joint surface, the type and number of shear keys, the thickness of epoxy resin coating, and other factors on the structural behavior and shear capacity of joints. Moustafa conducted an experimental study on segmental assembled I-beams, and found for the first time that the failure of epoxy resin joints occurred in concrete near epoxy resin, which verified the viewpoint that the crack strength of adhesive joints depends on the strength of plain concrete at the joints. Koseki and Breen from the University of Texas at Austin made an exploratory study on the shear properties of joints, encompassing several cases such as dry and adhesive joints, and their findings revealed that the application of epoxy resin could effectively increase the shear bearing capacity of the joints by 60% to 80%. A research team comprising Oral Buyukozturk, Mourad M. Bakhoum, and S. Michael Beattie of Massachusetts Institute of Technology performed a series of joint shear tests to evaluate the shear strength and deformation performance of precast segmental bridge joints, with the main parameters including the stress on the joint surface, the type of the joint and the coating thickness of epoxy resin adhesive. The results of these tests yielded several noteworthy conclusions: the shear strength of the adhesive joint is higher than that of dry joints, and the coating thickness of epoxy resin adhesive has no great influence on the strength and stiffness of key-tooth adhesive joint; the failure process of the dry joint and the adhesive joint is very sudden, which is a typical brittle failure; finally, through regression analysis of the test data, the research team derived direct shear strength formulas specific to different types of joints. M.A. Issa and H.A. Abdalla from the University of Illinois at Chicago [2] undertook a full-scale test on the single-bond tooth adhesive joint. The primary objective of their study was to examine the influence of two different types of epoxy resin adhesives on the shear properties of these joints. Furthermore, they performed a finite element analysis to derive their experimental conclusion that the shear strength of the joints coated with normal temperature curing epoxy resin adhesive is 28% higher than that coated with low temperature curing epoxy resin adhesive. Sowlat and Rabbat carried out an experimental study on three 1: 5 segmental precast T-section simply supported beams, considering three beams with internal bonding, external unbonded, and external partially bonded tendons. The results demonstrated that the inclusion of internal bonded prestressed tendons in the test beams enhanced their ductility, and the failure of segmental beams was primarily attributed to the shear failure of key teeth of shear keys.

In China, Zhou, Mickleborough, and Li [3] from the Hong Kong University of Science and Technology have experimentally researched the shear performance of plane joints, single-keyed joints, and three-keyed joints with reference to the experimental scheme of the Massachusetts Institute of Technology. The main conclusions of the test are as follows: the first crack usually appears at the bottom of the key and extends along the horizontal included angle of 45; the shear capacity of dry joints is less than that of adhesive joints. Guiding Code for Design and Construction of Segmental Precast Concrete Bridges published by the American Association of State Highway and Transportation Officials (AASHTO) underestimates the shear capacity of single-keyed joints, but overestimates the shear capacity of multi-keyed joints [3]. Wang [4] of the Bridge Research Institute of the Ministry of Railways carried out experimental research on shear keys between joints and did shear tests on three-keyed joint specimens and five-keyed joint specimens respectively. The test results show that the shear stress performance of the five-keyed joint is more favorable than that of the three-keyed joint, and the stress uniformity of the five-key joint is better than that of the three-keyed joint. Yuan [5] made an experimental study on the influence of different factors including preloading stress level, tooth pitch, tooth depth, and number of keys on the shear bearing capacity of joints, and the results revealed that the tooth pitch, tooth depth, and number of shear keys have little influence on the shear bearing capacity. The research conducted by Jiang [6] focused on the shear-bearing capacity of dry joints, considering various factors such as preloading stresses, tooth depths, tooth pitch and the number of keys, and pointed out that there are two cracking modes of single-keyed dry joints, and the failure mode of multi-keyed dry joints is manifested from top to bottom. Li [7] [8] empirically investigated the mechanical behavior of joints considering load, shear span ratio, joint type and other factors, and the results show that joints have no effect on the position and angle of inclined cracks in segmental failure in negative moment zone, and the failure of segmental precast simply supported box girder originates from the shear failure of concrete after joint opening.

The investigation of the aforementioned research on the shear performance of joints highlights that the crack resistance of joints depends on the strength of plain concrete at the joints. While factors such as prestress layout, stress levels, the number of shear keys, and epoxy resin coating thickness can improve joint bearing capacity to some extent, they are insufficient in addressing the underlying issue of brittle failure mode.

3 Research Status Research on Seismic Performance of Segmental Assembled Bridge Beams

Typically, in the context of overall cast-in-place prestressed concrete bridges, the seismic performance of the span structure is often overlooked, with the focus primarily placed on implementing measures to prevent beam collapse. However, for segmental precast and assembled bridges, the existence of joints weakens the seismic capacity of the span structure. As a consequence, there has been a notable emphasis on enhancing the seismic performance of the main girders in segmental precast bridges. The seismic performance of precast girder structures in segmental bridges has been the subject of considerable research in Europe, America, and Japan. These studies primarily employ large-scale model tests and finite element simulations to investigate the mechanical behavior of the joints between girder segments when subjected to seismic actions.

At present, the seismic test of segmental precast bridge girder mainly refers to the three-stage test frame proposed by Megally et al., University of California, San Diego [9–12]. The first stage of the test is aimed at the seismic performance of the joints in the middle of the main girder under the state of large bending moment and small shear force; in the second stage, the seismic performance of joints near fulcrum under large bending moment and large shear force is studied; the third stage test is directed toward the seismic performance of the bridge system with cast-in-place piers and segmental precast assembled main girders. The main girders in the test are all in the form of adhesive joints. The test results suggest that the epoxy resin glue layer itself will not crack under earthquake load, but the concrete around the glue joint will crack; under the seismic action, the joint has obvious nonlinear characteristics before failure; the anti-seismic performance of bonded prestressed segmental bridges is better than that of unbonded prestressed segmental bridges.

Veletzo, Restrepo and Aref [13–18] are the representatives of finite element analysis of seismic performance of joints of segmental prefabricated and assembled girders. The key findings are summarized as follows: under the influence of longitudinal earthquake forces alone, the joints predominantly exhibit elastic behavior; the combination of horizontal and vertical seismic forces leads to concrete cracks primarily concentrated at the joints, with the vertical component exerting a pronounced influence on the response of the joint; usually, joints located near the bridge piers and mid-span areas often experience significant displacement demands, and following an earthquake event, all the joints between the segments tend to close again.

Studies involving tests and finite element analysis shed light on the seismic performance of adhesive joints. The findings consistently reveal that the epoxy resin adhesive layer remains intact during earthquakes. Nevertheless, noticeable cracking occurs in the plain concrete adjacent to the adhesive joint. This cracking phenomenon is followed by distinctive nonlinear characteristics in the joint.

4 Calculation Method for Shear Resistance of Segmental Precast Bridge Joints

From the point of view of practical engineering application, if the formula for design and calculation is put forward on the basis of experiments, the complex calculation and analysis will become simple, and many scholars have also carried out a lot of research in this field. In the aspect of joint direct shear calculation, AASHTO [19] gives the calculation formula of direct shear strength of shear key in dry joints as follows:

$$V = A_{\mathrm{k}}\sqrt{6.792 \times 10^{-3} f_{cm}}(12 + 2.466\sigma_n) + \mu \cdot A_{sm} \cdot \sigma_n \text{ (MPa)} \quad (1)$$

In the formula, f_{cm} refers to the feature value of concrete compressive strength, σ_n means the preloading stress of the shear key section, A_k indicates the area of all shear key roots, A_{sm} denotes the contact area of the non-keyed part of the failure surface, and μ represents the friction coefficient of concrete, taken as 0.6.

The AASHTO code distinctly categorizes the shear-bearing capacity of joints into two distinct components. The first component pertains to shear key bearing, while the second component is associated with concrete friction bearing. Zhou [3], Issa [6], and Turmo [20] used experimental data to verify the formula, and the results show that the formula is conservative. Lu [21] analyzed the AASHTO formula, and believed that the irrationality of this formula lies in three aspects: it is unreasonable to divide the failure surface into two parts according to geometric shape; the physical meaning of the first term of the formula is unclear; the consideration of multi-tooth shear keys is unclear. Consequently, through the analysis of test data and finite element analysis, he put forward the calculation formula of shear strength, which is in good agreement with the test results. In addition, Buyukozturk, Moustafa, and Liu Zhao [22] also present direct shear calculation formulas for dry joints and adhesive joints. In the calculation of bending and shear strength of joints, the AASHTO code also gives the calculation formula of shear strength:

$$V_u \leqslant \phi V_u = \phi(V_c + V_s) \tag{2}$$

In the formula, V_c is the nominal shear force borne by concrete, V_s is the nominal shear force borne by the stirrup, and ϕ is the strength reduction factor, taken as 0.85. Li [7] and Yuan [5] utilized the test data to calculate the strength of this formula, and the results indicated that there was a big error between the test results and the AASHTO code. In addition, Professor Li [23] derived the calculation formula for the shear-bearing capacity of the joint section based on the biaxial strength theory of concrete and the limit equilibrium condition of the joint section and verified the calculation formula with experimental data, The results show that the calculated value is lower than the measured value, and the results are safe, which can better reflect the change law of the shear strength of the joint section.

$$V = \phi\left(\frac{0.22 + 0.026\text{m} - 0.22\text{m}V_\text{P}/T_{ps}}{0.5 + 0.22\text{m}\frac{f_\text{ck}bh_0}{T_\text{ps}}} - 0.12\frac{T_\text{ps}}{f_\text{ck}bh_0}\right)f_\text{ck}bh_0 + V_\text{p} \tag{3}$$

In the formula, ϕ is the reduction factor, m is the shear span ratio, V_P is the prestressed reinforcement shear bearing capacity, T_ps is the tensile steel bars ultimate tensile force, f_ck is the concrete compressive strength, b is the web width, h_0 is the distance from the tensile reinforcement section to the compressive edge.

Some scholars have studied the failure mechanism and calculation model of concrete shear bonds from the perspective of fracture mechanics and put forward theoretical analytical calculation methods. Kaneko proposed to employ a separate crack model and a diffuse crack model to analyze the stress of dry joints of shear keys between plain concrete and fiber-reinforced concrete, and pointed out that the mechanism of shear key shedding lies in the formation of S Crack and M Crack. He also put forward the theoretical analytical calculation model and calculation method, and the analysis results can better predict the structural behavior of joints. However, this model is not easy for engineers to master, and its guiding role in engineering design is limited.

5 Conclusions

Although the segmental bridge has obvious advantages in construction speed and ease of construction, there is a need for further study to address some defects and deficiencies present in the joints, which is mainly manifested in the following aspects:

(1) The crack resistance of joints predominantly counts on the strength of plain concrete at the joints. Regardless of factors such as prestress layout, stress, number of shear keys, or thickness of epoxy resin coating, while these may enhance the load-bearing capacity of joints to some extent, they cannot address the inherent brittle failure mode of joints when subjected to the ultimate state of shear bearing capacity.
(2) Under seismic conditions, the concrete surrounding the adhesive joint tends to develop cracks as a response to the earthquake forces. As these cracks propagate over time, the joint's failure mode assumes similarities to that of the adhesive layer itself. Notably, the epoxy resin adhesive layer remains intact and does not undergo tearing or separation. Within the joint, the plain concrete shear keys may exhibit brittle failure characteristics, which can lead to a sudden detachment of the beam body. Additionally, the joint displays distinct nonlinear characteristics prior to failure.
(3) At present, the calculation formula for the shear design of segmental precast bridge joints has some shortcomings, such as unclear physical meaning and a lack of convenience for engineers to grasp. Consequently, its efficacy as a guiding tool for engineering design is constrained, highlighting the need for further enhancements and refinements to address these limitations.

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