Experiment of Shear Performance of Epoxy Resin Joints with Single Keys in Precast Concrete Segmental Bridges

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Abstract: In order to research the effect of epoxy resin thickness on the shear capacity of the epoxy resin joints of precast concrete segmental bridges, segmental bridges, one group of 6 full-depth single shear key specimens were cast and tested. Based on the experimental results, ultimate shear loads were recorded, cracking patterns and failure modes were observed. The normalized shear stress-vertical relative slip curves were investigated, and some design formulas for assessing the shear capacity of epoxy resin joints were compared and analysed. It is found that the thicker the epoxy resin thickness with the single keys is, the higher the shear capacity of epoxy resin joints is, the larger the normalized shear stress is, and the better plastic deformation capacity of epoxy resin joints is. BUYUKOZTURK O formula overestimates the shear capacity of epoxy resin joints with single keys, and several other design formulas underestimate shear capacity of epoxy resin joints with single keys; it is not appropriate to ignore the effect of epoxy resin thickness on the shear capacity of the epoxy resin joints.

1. Introduction
Segment prefabrication and rapid construction technology is increasingly used in bridge construction and is widely used in highway bridges, railway bridges, and urban municipal bridges [1]. The standard segment prefabrication technology can not only meet the requirements for rapid construction of the bridge, but also have significant advantages such as economy, safety, small disturbance to the natural environment. In this type of bridge, ordinary steel bars are broken at the joints, and the precast concrete segments are connected by prestressing tendon [2]. The joints have complex mechanical behavior, and they are also the weak part of the precast concrete segmental bridges, which have a significant impact on the structural mechanical behavior of the precast concrete segmental bridges.

The American Association of State Highway and Transportation Officials code [3] considers the effect of the precast segment joints on the strength of the bridges. The code divides the precast segment joints into Class A joints and Class B joints, Class A joints include wet joints and epoxy resin joints, and Class B joints are dry joints. Epoxy resin guarantees the uniformity of the stress on the joints, improves the durability of the joints, and can compensate for the errors in the matching of the male-female shear keys. Therefore, it is stipulated in the AASHTO code that all newly built precast concrete segmental bridges can only use Class A joints [4].

For the shear performance of epoxy resin joints, a lot of experimental researches were tested by many scholars. S. Kuranish et al. [5] carried out the experiment of shear capacity of epoxy resin joints,
and pointed out that the shear capacity of rough surface specimens was larger than that of smooth surface specimens. BUYUKOZTÜRK O et al. [6] found that the shear capacity of epoxied joints is consistently higher than that of dry joints. However, the failure of the epoxied joints was found to be very sudden and brittle. ISSA MA [7] proved that the observed failure mode of all shear-key specimens was fracture of concrete along the joints with shearing of the keys. The epoxy resin can significantly improve the shear capacity of epoxy-jointed single keys, the hot-weather epoxy specimens showed an increase of about 28% in the shear capacity, in comparison to the cold-weather epoxy specimens. Li Guoping [8] used the shear-span ratio, stirrup ratio, joint type, ratio of internal tendons to external tendons and other parameters to conduct 13 monolithic and 14 segmental (epoxy jointed and dry jointed) simply-supported externally prestressed concrete model beam test. The results show that there is significant difference in shear behavior between segmental externally prestressed concrete beams and monolithic beams. Yuan Aimin et al. [2, 9] found that the shear capacity of epoxy resin joints has no correlation with depth and space of shear key. The layout of internal tendons crossing the joint and reinforcing bar in keys not only enhanced the ductility of the epoxy resin joints but also decreased the ratio of crack shear load to ultimate shear load, and even changed the crack pattern.

At present, many factors have been researched on the shear performance of epoxy resin joints in Precast Concrete Segmental Bridges, including concrete type, joint type, ambient temperature, geometrical size of the key, horizontal confining stress, and many important achievements have been made in the calculation of shear capacity and strength, but the research on the influence of thickness of epoxy resin on shear capacity of epoxy joints is less. Meanwhile, the thickness of epoxy resin joints of precast concrete segmental bridges is different. Whether the previous research results can be applied, it is necessary to conduct a systematic study on this. In this paper, the epoxy resin thickness is used as the key factor to study the cracking modes, the law of ultimate shear loads and vertical relative slip of epoxy resin jointed specimens under direct shear. Some design formulas for assessing the shear capacity of epoxy resin joints were evaluated.

2. Experimental studies

2.1. Experimental design
In order to study the transmission of shear force along the jointed surface, the shape of the specimens should be as close as possible to the shear force transmission mode of precast concrete segmental bridge joint surface, the uniformity of the shear force distribution on the joint surface and the loading test are considered comprehensively. Based on the existing test data, the full-depth single shear key specimens of type Z are match cast and tested. During the specimen loading process, stress concentration at the loading point and corner of the specimen will cause local concrete crushing. In order not to cause the other parts of the specimens to break before the joint surface, it is reinforced by placing structural steel bars. Figure 1 and Table 1 give the dimensions and configurations of the Z-shaped specimens respectively.

![Figure 1. Specimen dimensions and configurations for shear-key test.](image)
Table 1. Information of the specimens.

| Number | Type                                | Epoxy resin thickness (mm) | Depth of key (mm) | Top width of key (mm) | Bottom width of key (mm) | Dimensions (mm) |
|--------|-------------------------------------|----------------------------|-------------------|-----------------------|--------------------------|-----------------|
| B1     | Epoxy resin joints with single keys | 1.0                        | 35                | 50                    | 100                      | 540×340×150      |
| B2     | Epoxy resin joints with single keys | 3.0                        | 35                | 50                    | 100                      | 540×340×150      |
| B3     | Epoxy resin joints with single keys | 8.0                        | 35                | 50                    | 100                      | 540×340×150      |

2.2. Material properties

The concrete design strength grade for this test is C50. The mass ratio of cement, fly ash, sand, medium stone, pebble, water, and water reducing agent is 358:63:768:815:203:169:1, of which the water-cement ratio is 0.31. 18 cube test blocks with a size of 100mm×100mm×100mm were mixed. The average value of the compressive strength of the cube was 59.87MPa, which meets the requirements of C50 concrete. The concrete for testing the mechanical properties is the same batch as the concrete for casting the specimens. In this test, twisted steel bars were used as the structural reinforcement of the specimens. The diameter of the steel bars is 12 mm, the yield strength is 335 MPa, and the elastic modulus was 2.0×10⁵ MPa. The specimens are divided into female keys and male key. The specimens are divided into two parts using wooden formworks and precast steel partitions. The female keys and the male keys are cast at the same time. After the concrete strength of the specimens reaches 80% of the design strength, the test requires that the epoxy resins are spread evenly on the surface of the specimens with scrapers. It must be spliced within two hours. The assembled specimens are placed in the environment of 20-40°C for 24 hours. The manufacturing process of the specimens is shown in Figure 2.

Figure 2. Manufacturing process of the specimens.
2.3. Test setup

In this test, a 2000kN hydraulic servo testing machine was used for the push-out test of epoxy resin joints with single keys. The loading method used displacement control, and the loading rate did not exceed 0.5mm/min. The Typical experimental setup is shown in Figure 3. (1) Vertical loading device: A linear displacement meter is placed on the loading end of the pressure oil cylinder and the specimens base to collect vertical relative slip. A sensor is placed at the loading end of the vertical load pressure head, and a steel plate is placed under the sensor to uniformly transmit the force, and the pressure signal is synchronized with the displacement meter signal. (2) Horizontal loading device: In order to simulate the prestressing effect between precast segmental concrete bridge sections, horizontal loading devices are arranged on both sides of the test piece. The device consists of a special steel restraining hoop, two steel plates, a polyvinyl chloride plastic plate, a small pressure sensor, and a hydraulic jack. The steel restraining hoop includes four steel bars. The steel bars pass through the restraint steel plates placed on both sides of the specimen to control the loading area. The concentrated force is converted into horizontal normal stress and uniformly transmitted to the jointed surface. Inside the steel plate, a polyvinyl chloride plastic plate is placed, and the side of the plastic plate is coated with lubricating oil, thereby eliminating the frictional force of the upper shear key during the downward movement. In the shear key test, a hydraulic jack is used to apply lateral preload on the horizontally constrained steel plate to prevent the shear key specimen from slipping during the push process. The lateral normal stress is set to 0.1 MPa during the test. (3) Data acquisition system: The vertical load data is collected by the control system that comes with the testing machine. The vertical relative slip data is collected by a data acquisition instrument produced by Jiangsu Donghua Testing Technology Co., Ltd.

The load applied by the test specimen is mainly divided into two parts: vertical load and horizontal load. Horizontal load is used to simulate the normal stress caused by tensioning the prestressing tendon in the actual project. In the test, the horizontal load reaches a predetermined value by controlling the separated hydraulic jack. The vertical load is divided into two parts: preloading and formal loading. The preloading part adopts load control. After the preloading, the formal loading test starts. The formal loading part uses displacement control. The loading rate is 0.5mm / min until the component is crushed. The duration after each stage of displacement is added, the strain is read after the value is stable, the slip of the male and female teeth and the development of cracks are observed. Because this test is a destructive test, there is no need to measure the residual deformation and residual stress of the component after the test, so the unloading process is not carried out in stages, and it is unloaded slowly to zero.

Figure 3. Typical experimental setup.
3. Experimental results

3.1. Summary of experimental results
Three types of epoxy resin jointed specimens with single keys were tested in the experiment. The experimental results of the specimens under concentrated load are summarized in Table 2. In order to ensure the accuracy of the test results, two identical specimens were made for each specimen, and two identical specimens with the same loading conditions were tested. The experimental results were compared with each other. The average of the experimental data of two identical specimens was finally synthesized a curve.

| Number | Ultimate shear load (kN) | Shear area (m²) | Relative vertical slip (mm) | Ultimate shear stress (MPa) | Normalized shear stress | Mean normalized shear stress |
|--------|-------------------------|----------------|----------------------------|-----------------------------|------------------------|-----------------------------|
| B1-1a  | 150.98                  | 0.03           | 0.46                       | 5.03                        | 0.73                   | 0.75                        |
| B1-2a  | 157.22                  | 0.03           | 0.47                       | 5.24                        | 0.76                   | 0.86                        |
| B2-1a  | 173.86                  | 0.03           | 0.50                       | 5.80                        | 0.84                   | 0.88                        |
| B2-2a  | 181.62                  | 0.03           | 0.52                       | 6.05                        | 0.88                   | 0.88                        |
| B3-1a  | 179.83                  | 0.03           | 0.53                       | 5.99                        | 0.87                   | 0.87                        |
| B3-2a  | 182.63                  | 0.03           | 0.53                       | 6.09                        | 0.89                   | 0.89                        |

*B-1 or B-2 indicates that two identical specimens with the same loading conditions were tested.

3.2. Experimental failure modes
In this paper, the experimental phenomenon description and analysis are performed for some representative specimens in this test. The failure mode of B1-1 is shown in Figure 4. When the load was increased in the early stage, no cracks appeared in the joint area of the specimen. When the vertical load reaches 150.98kN, the internal micro-cracks increase sharply under high stress, resulting in a main crack, and a small amount of micro-cracks near the main crack. After the shear load reached the shear capacity, the vertical relative slip was about 0.46mm at this time. In the end, the specimen slipped and the concrete on the surface of the joint area was peeled. The other areas of the specimen were crushed during the test. After the specimen was broken, the epoxy resin in the weak area was still intact, and the specimen mainly cracked along the concrete area. The failure process of the specimen is rapid without obvious signs, and the sound is loud when it is broken, which belongs to the brittle failure type.

![Figure 4. failure mode of the specimens.](image_url)
3.3. Analysis of experimental parameters

In order to eliminate the influence of concrete strength factors on shear resistance, the concept of standardized shear stress widely used by the American Highway and Transportation Association (AASHTO) and the American Certification Association (ACI) was introduced when processing experimental data. $\tau_n = \frac{\tau}{\sqrt{f'_c}}$ is the ratio of the shear stress $\tau$ to the arithmetic square root of the compressive strength $f'_c$ of the concrete cylinder. When the strength grade of the concrete is C50, the compressive strength $f'_c$ of the concrete cylinder can be approximated by 0.79 times the cubic compressive strength $f_{cu}$, and shear stress $\tau$ is defined as the shear stress divided by the shear area.

From the data in Table 2, it can be seen that the ultimate shear loads of B1-1 and B1-2 are 150.98kN, 157.22KN, the ultimate shear loads of B2-1 and B2-2 are 173.86kN and 181.62kN, and the ultimate shear loads of B3-1 and B3-2 are 179.83kN and 182.63kN. The average shear capacity of specimens B3-1 and B3-2 is increased by 17.6% compared to the average shear capacity of specimens B1-1 and B1-2. The average shear capacity of specimens B3-1 and B3-2 is increased by 2.0% compared to the average shear capacity of specimens B2-1 and B2-2. The vertical relative slips of B1-1 and B1-2 are 0.46mm, 0.47mm, the vertical relative slips of B2-1 and B2-2 are 0.50mm, 0.52mm, and vertical relative slips of B3-1 and B3-2 are 0.53mm, 0.53mm. The average vertical relative slip of specimens B3-1 and B3-2 was increased by 14.0% compared to the average vertical relative slip of specimens B1-1 and B1-2. The average vertical relative slip of specimens B3-1 and B3-2 was increased by 3.9% compared to the average vertical relative slip of specimens B2-1 and B2-2. The comparison test results show that the thicker the epoxy resin with single keys is, the higher the shear capacity of epoxy resin joints is, and the better its plastic deformation capacity of epoxy resin joints is.

Figure 5 showed the normalized shear stress-vertical relative slip curves for B1, B2, and B3. It can be found that the failure modes of the specimens of B1, B2, and B3 are the same. Before reaching the ultimate shear strength, the normalized shear stress-vertical relative slip curve changes linearly, and the normalized shear stress-vertical relative slip curve slope is basically Similar. After shear failure, the curve no longer rises to maintain the level, the slope is approximately zero, and the vertical relative slip continues to increase. The normalized shear stress and vertical relative slip of B3 are the largest, the normalized shear stress and vertical relative slip of B2 are the second, the normalized shear stress and vertical relative slip of B1 are the smallest. From 1mm to 3mm, the normalized shear stress increases greatly. From 3mm to 8mm, the normalized shear stress increases less. In summary, the normalized shear stress of the epoxy resin joints with single keys increases with the thickness of the epoxy resin.

![Figure 5. Normalized shear stress-vertical relative slip curves.](image-url)
4. Comparisons of existing formula

Scholars have researched the shear performance of epoxy resin joints with keys, and put forward some calculation formulas for the shear capacity of epoxy resin joints with keys under direct shear. Among them, the calculation formula proposed by BUYUKOZTURKO et al. [6] is a semi-empirical and semi-theoretical formula obtained by regression analysis using mathematical statistics methods based on rich experimental data. The calculation formula proposed by Lu Wenliang [10] is based on the fact that the shear capacity of joints is provided by the friction and shear resistance of full-section concrete. The correctness of this premise needs to be verified, because the shear capacity will be determined by the larger of the frictional resistance and the shear resistance of the full-section concrete. The calculation formula proposed by Sun Xueshuai [11] researched the direct shear failure mechanism of joints and the calculation method of bearing capacity, and introduced the reduction coefficient of multi-keys to consider the effect of uneven force on multi-keys. The calculation formula proposed by Yuan Aimin [2] is based on the Mohr-Coulomb friction failure criterion and can be used to evaluate the shear strength of shear joints in epoxy resin joints, and the formula parameters are modified by combining ACI and AASHTO specifications.

The formula for calculating the shear capacity of epoxy resin joints with single keys proposed by BUYUKOZTURKO et al. is:

$$V_a = A_f (0.921 \sqrt{f_c} + 1.20 \sigma_n)$$

(1)

Where: $\sigma_n$ is the normal stress of the joint surface (MPa); $A_f$ is the total shear area of the jointed surface of shear keys (mm²).

The formula for calculating the shear capacity of epoxy resin joints with single keys proposed by Lu Wenliang is:

$$V_b = A_f (0.6 \sqrt{f_c} + 0.83 \sigma_n)$$

(2)

The formula for calculating the shear capacity of epoxy resin joints with single keys proposed by Sun Xueshuai is:

$$V_c = \alpha_1 A_f (0.39 f_{cu}^{2/3} + 1.51 \sigma_n)$$

(3)

Where: $\alpha_1$ is the direct shear reduction coefficient of epoxy resin joints with shear keys, and it is recommended to take 0.8; $\alpha$ is the multi-key reduction coefficient. When the number of shear keys is 1 to 2, it is recommended to take 1.0.

The formula for calculating the shear capacity of epoxy resin joints with single keys proposed by Yuan Aimin is:

$$V_d = \alpha A_{joint}^{eq} (0.56 \sqrt{f_c} + 1.2 \sigma_n)$$

(4)

Where: $\alpha$ is the coefficient considering the number of shear keys., The $\alpha$ of single key and multi-key is 1.1 and 0.9 respectively; $A_{joint}^{eq}$ is the converted cross-sectional area, $A_{joint}^{eq} = A_f + (n - 1) A_s$, where $A_s$ is the reinforcement area (mm²). Because the shear keys tested in this paper are plain concrete, so $A_s$ is taken as 0.

The ultimate shear load measured by the direct shear test of all specimens was compared with the calculated values of formulas (1) to (4), and the results are shown in Table 3. It can be seen that, for the specimens of epoxy resin joints with single keys, the average values of the ratios of the measured values of the test ultimate shear load to the calculated values of equations (1) to (4) are 0.88, 1.35, 1.16, and the variances are 0.004, 0.010, 0.007, and 0.009. It is shown that formula (1) overestimates the shear capacity of the specimens of epoxy resin joints with single keys, and formulas (2) to (4) underestimate the shear capacity of the specimens of epoxy resin joints with single keys, and the fluctuation of the ratio of the measured value of the test ultimate shear load to the calculated value of formula (1) is the smallest. The ratio of the measured value of the test ultimate shear load to the
calculated value of formula (1) is 0.78, 0.81, 0.90, 0.94, 0.93, 0.94, and the ratio of the measured value of the test ultimate shear load to the calculated value of formula (2) is 1.20, 1.25, 1.38, 1.44, 1.42, 1.45, the ratio of the measured value of the test ultimate shear load to the calculated value of formula (3) is 1.03, 1.07, 1.18, 1.24, 1.22, 1.24, the ratio of the measured value of the test ultimate shear load to the calculated value of formula (4) is 1.15, 1.20, 1.33, 1.39, 1.37, and 1.39. It is shown that when the thickness of the epoxy resin is 1mm, formula (3) has the best prediction effect on the shear capacity of the epoxy resin joints with single keys, and when the thickness of the epoxy resin is 8mm, formula (1) has the best prediction effect on the shear capacity of the epoxy resin joints with single keys.

Footnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

Table 3. Comparisons of existing formula.

| Number | $f_c$/MPa | $V_a$/KN | $V'_a$/KN | $V_a/V_a$ | $V_a/V_b$ | $V_c$/KN | $V_a/V_c$ | $V_d$/KN | $V_a/V_d$ |
|--------|-----------|----------|-----------|-----------|-----------|----------|-----------|----------|-----------|
| B1-1   | 47.30     | 150.98   | 193.62    | 0.78      | 1.20      | 146.87   | 1.03      | 131.05   | 1.15      |
| B1-2   | 47.30     | 157.22   | 193.62    | 0.81      | 1.25      | 146.87   | 1.07      | 131.05   | 1.20      |
| B2-1   | 47.30     | 173.86   | 193.62    | 0.90      | 1.38      | 146.87   | 1.18      | 131.05   | 1.33      |
| B2-2   | 47.30     | 181.62   | 193.62    | 0.94      | 1.44      | 146.87   | 1.24      | 131.05   | 1.39      |
| B3-1   | 47.30     | 179.83   | 193.62    | 0.93      | 1.42      | 146.87   | 1.22      | 131.05   | 1.37      |
| B3-2   | 47.30     | 182.63   | 193.62    | 0.94      | 1.45      | 146.87   | 1.24      | 131.05   | 1.39      |
| Average|           |          |           | 0.88      | 1.35      | 1.16     | 1.31      |          |           |
| variance|          |          |           | 0.004     | 0.010     | 0.007    | 0.009     |          |           |

5. Conclusions

By studying the shear performance of precast segmented glued joints under direct shear and considering the thickness of epoxy resin, the following conclusions are drawn:

(1) The thicker the epoxy resin thickness with single keys is, the higher the shear capacity of epoxy resin joints is, the larger the normalized shear stress is, and the better plastic deformation capacity of epoxy resin joints is.

(2) The BUYUKOZTURK O formula overestimates the shear capacity of shear capacity of epoxy resin joints with single keys, and the Lu Wenliang, Sun Xueshua, and Yuan Aimin formula underestimate the shear capacity of the epoxy resin joints with single keys. When the thickness of the epoxy resin is 1mm, the Sun Xueshuai formula has the best prediction of the shear capacity of the epoxy resin joints with single keys; when the thickness of the epoxy resin is 8mm, the BUYUKOZTURK O formula has the best prediction of the shear capacity of the epoxy resin joints with single keys.

(3) The calculation formula of the shear capacity of the epoxy resin joints with shear keys proposed by most scholars today generally does not take into account the thickness of the epoxy resin. Therefore, the calculation formula of the shear capacity of the epoxy resin joints with shear keys can accurately predict the shear capacity of the epoxy resin joints with shear keys only under the specified thickness of the epoxy resin.

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