Shear Behavior of Prefabricated Segmental Epoxied Joints Considering Defect Degree in Cemented Surfaces

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Abstract: In order to research the influence of the defect degree of cemented surface on the shear behaviour of prefabricated segmental epoxied joints, the paper considers the defect degree of cemented surfaces on the specimens of epoxied joints with single keys by direct shear test and records the ultimate shear loads and vertical relative slips, the failure modes of the specimens and the normalized shear stress-vertical relative slip curve are analysed, and the measured values of the ultimate shear loads are compared with the existing calculation formula. It can be concluded that the shear capacity, normalized shear stress and plastic deformation capacity of the specimens of epoxied joints with single keys without defect in the cemented surfaces have been improved which are compared with the specimens with 10% defects and the specimens with 20% defects. The BUYUKOZTURK O formula overestimates the shear capacity of the specimens with 10% defects, and underestimates the shear capacity of the specimens with no defects and 10% defects; The formulas of Sun Xueshuai and Yuan Aimin underestimate the shear capacity of the specimens with no defects, 10% defects and 20% defects. It is not appropriate to ignore the effect of the defect degree in the cemented surface on the shear capacity of the epoxied joints.

1. Introduction

The conception, development and worldwide acceptance of segmental construction in the field of precast concrete segmental bridges represent one of the most interesting achievements in civil engineering[1]. The joints, which are the weakness of the precast segment concrete bridges, is one of the important factors that affects the whole behavior of the precast segment concrete bridges. Therefore, it is very necessary to conduct experimental research on its shear behavior[2]. 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 and divides the precast segment joints into Class A joints and Class B joints. Class A joints include epoxied joints and wet joints. Class B joints are dry joints. Epoxied 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].

Many scholars did a lot of experimental researches to test the shear behavior of prefabricated segmental epoxied joints. S. Kuranish et al. [5] carried out the experiment of shear capacity of epoxied joints and pointed out that the shear capacity of rough surface specimens was larger than the shear capacity of smooth surface specimens. BUYUKOZTÜRK O et al. [6] conducted an experimental study on the shear capacity and plastic deformation capacity of prefabricated segmental joints, It was found that the strength 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 epoxied resin
can significantly improve the shear capacity of epoxied-jointed single keys, the hot-weather epoxied specimens showed an increase of about 28% in the shear capacity in comparison to the cold-weather epoxied specimens. Ahmed G H et al.\cite{1} found that the shear capacity of all types of joints increases with an increase in confining stress, and contribution of concrete compressive strength in joint shear strength is higher for weaker concrete classes.

At present, many factors have been researched on the shear behavior of prefabricated segmental epoxied joints including concrete type, ambient temperature and horizontal confining stress but there are few researches on the shear behavior of the defect degree of cemented surface to epoxied joints. Meanwhile, the defect degree of epoxied joints of precast concrete segmental bridges is different, Whether the previous research results can be applied, it is necessary to conduct a systematic study. In this paper, the defect degree of cemented surface is used as the key factor to study the failure modes, the law of ultimate shear loads and vertical relative slip of epoxied jointed specimens under direct shear and the calculation formulas proposed by some scholars are compared and analyzed.

2. Experimental studies

2.1. Experimental design

In order to make the shape of the specimens as similar as possible to the shear force transmission mechanism of the epoxied joints, the Z-type specimens were used to analyze the shear behavior of the epoxied joints. In order not to damage the other parts of the specimens before the joint surface, it is strengthened by configuring structural steel bars. The thickness of all specimens is 150mm. Figure 1 and Table 1 respectively give the specific dimensions and construction of the Z-type specimens.

![Figure 1. Specimen dimensions and configurations for shear-key test.](image)

| Number | Type                          | Epoxied resin thickness (mm) | defect degree (%) | Dimensions (mm) |
|--------|-------------------------------|------------------------------|-------------------|-----------------|
| Q1     | Epoxied joints with single keys | 8.0                          | 0                 | 540×340×150     |
| Q2     | Epoxied joints with single keys | 8.0                          | 10                | 540×340×150     |
| Q3     | Epoxied joints with single keys | 8.0                          | 20                | 540×340×150     |

2.2. Material properties

The concrete design strength grade for this test is C60. In this test, threaded steel bars were used as the structural reinforcement of the specimens. The steel bar diameter was 12 mm, the yield strength was 335 MPa. The specimens were divided into male keys and female key, which were separated by prefabricated steel partitions and wooden formworks. Both keys were cast at the same time. After the concrete strength of the specimens reaches the design strength, the epoxied resins are spread evenly on
the surface of the specimens. The assembled specimens are placed in the environment of 20-40°C for 7 days. The detailed process of the specimens is shown in Figure 2.

![Figure 2](image1.png)

**Figure 2. Detailed process of the specimens.**

The test used 3D printing technology to print the resin material into a hollow cylinder to simulate the defects caused by the cemented surfaces. The cylinders were the same size with 8mm height and 4mm radius. The test needed to fix the simulated defect cylinder on the surface of male keys through rapid hardening glue. The layout of the defect degree of cemented surface is shown in Figure 3.

![Figure 3](image2.png)

**Figure 3. Layout of the defect degree.**

2.3. **Test setup**

(1) Vertical loading device: The experimental vertical loading device adopts 2000kN hydraulic servo testing machine. In order to make the specimens evenly stressed, a steel plate is placed under the sensor at the load end of the vertical load, and the vertical displacement meter collects the vertical relative slip.

(2) Horizontal loading device: In order to simulate the prestress effect between the bridge segments, the horizontal loading device was arranged on both sides of the specimens. The device consisted of steel hoop, steel plate, PVC plastic board, small pressure sensor and hydraulic jack. The hydraulic jack applies horizontal preload on the horizontal steel plate, and the horizontal normal stress is set to 0.3 MPa.

(3) Data acquisition equipment: The vertical load and vertical relative slip are collected by a static data acquisition device produced by Donghua Test Technology Co., Ltd. The Typical experimental setup is shown in Figure 4.

![Figure 4](image3.png)

**Figure 4. Typical experimental setup.**

In the test, the separated hydraulic jack is controlled to make the horizontal load reach the predetermined value. Before the specimens are officially loaded, the specimens are preloaded, and it is unloaded to enter the formal loading test after preloading. During the formal loading of the test, the displacement-controlled loading mode is used, and the loading rate is 0.5 mm/min until the specimens are crushed. After the displacement of each level is added, the strain is read after the value is stabilized, the development of cracks and the slip of the female keys and male keys are observed.

3. **Experimental results**

3.1. **Summary of experimental results**
The test researched epoxied resin jointed specimens with different defect degree. The test results of the specimens are summarized in Table 2.

| Number | Ultimate load (kN) | Shear area (m²) | Relative vertical slip (mm) | Ultimate shear stress (MPa) | Normalized shear stress | Mean normalized shear stress |
|--------|--------------------|----------------|-----------------------------|-----------------------------|------------------------|----------------------------|
| Q1-1a  | 281.55             | 0.03           | 0.4889                      | 9.3850                      | 1.2257                 | 0.75                       |
| Q1-2a  | 279.48             | 0.03           | 0.4989                      | 9.3160                      | 1.2167                 | 0.75                       |
| Q2-1a  | 260.44             | 0.03           | 0.4728                      | 8.6813                      | 1.1338                 | 0.86                       |
| Q2-2a  | 264.94             | 0.03           | 0.4880                      | 8.8313                      | 1.1534                 | 0.86                       |
| Q3-1a  | 203.04             | 0.03           | 0.3905                      | 6.7680                      | 0.8839                 | 0.86                       |
| Q3-2a  | 193.71             | 0.03           | 0.4265                      | 6.4570                      | 0.8433                 | 0.86                       |

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

3.2. Experimental failure modes

In this paper, the experimental phenomenon description and analysis are performed for some representative specimens in this test, and the failure mode of Q2-1 is shown in Figure 5. When the vertical load increased in the early stage, there was no crack on the surface of the specimen, when the vertical load reached the ultimate shear capacity of 260.44kN, the internal micro-cracks increased rapidly under high stress, and two main cracks were generated, a small number of micro-cracks were generated near the main cracks. In the end, the specimen sheared and slipped along the root of the key, and the concrete on the joint area did not peel off.

3.3. Analysis of experimental parameters

In the data processing of this experiment, the concept of normalized shear stress widely adopted by the American Certification Association (ACI) and the American Highway and Transportation Association (AASHTO) was introduced. \( \tau_n = \tau / \sqrt{f'_c} \) 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 C60, the compressive strength \( f'_c \) of the concrete cylinder can be approximated by 0.833 times the cubic compressive strength \( f_{cu} \).

From the data in Table 2, it can be seen that the average shear capacity of Q2-1 and Q2-2 is reduced by 6.35% and Q3-1 and Q3-2 is reduced by 29.28% compared to the average shear capacity of Q1-1 and Q1-2. The average vertical relative slip of Q2-1 and Q2-2 is reduced by 2.73% and Q3-1 and Q3-2 is reduced by 17.29% compared to the average vertical relative slip of specimens Q1-1 and Q1-2. By comparing the test results, it can be concluded that the shear capacity of the specimens of epoxied joints with single keys without defect in the cemented surfaces is higher than the specimens with 10% defects and the specimens with 20% defects, its plastic deformation ability is also the best.

Figure 6 shows the normalized shear stress-vertical relative slip curves for Q1, Q2, and Q3. It can be seen from the figure 6 that the normalized shear stress-vertical relative slip curves of Q1, Q2, and Q3 have an ascending phase and a descending phase. Before the shear failure of the specimens, the normalized shear stress increases continuously with the increase of the vertical relative slip, the slope of Q1 is the largest, followed by Q2, and finally Q3. After the shear failure of the specimens, the normalized shear stress decreases as the vertical relative slip increases, the slope of Q1 is the largest, followed by Q2, and finally Q3. Q1 has the largest normalized shear stress, Q2 has the second normalized shear stress.
stress, and Q3 has the smallest normalized shear stress. In summary, the normalized shear stress of the specimens of epoxied joints with single keys without defect in the cemented surfaces is higher than the specimens with 10% defects and the specimens with 20% defects.

![Figure 6. Normalized shear stress-vertical relative slip curves.](image)

### 4. Comparisons of existing formula

Some scholars have researched the shear behaviour of epoxied joints, and have proposed some calculation formulas for the shear capacity of epoxied joints under direct shear. This paper compares and analyses the calculated values of the formulas proposed by some scholars. The comparisons of existing formula are shown in Table 3.

BUYUKOZTURK O et al. [6] proposed the calculation formula of the shear capacity of epoxied joints:

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

(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).

Sun Xueshuai [8] proposed the calculation formula of the shear capacity of epoxied joints:

\[ V_b = \alpha_3 \alpha A_f (0.39 f_{cu}^{2/3} + 1.51 \sigma_n) \]  

(2)

Where: \( \alpha_3 \) is the direct shear reduction coefficient of epoxied joints, 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.

Yuan Aimin [9] proposed the calculation formula of the shear capacity of epoxied joints:

\[ V_c = \alpha A_{joint}^{eq} (0.56 \sqrt{f_c} + 1.2 \sigma_n) \]  

(3)

Where: The \( \alpha \) of single key is 1.1; \( A_{joint}^{eq} \) 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 take 0.

| Number | \( f_c/\text{MPa} \) | \( V_a/\text{KN} \) | \( V_b/\text{KN} \) | \( V_a/V_a \) | \( V_b/V_b \) | \( V_a/V_b \) | \( V_c/\text{KN} \) | \( V_a/V_c \) |
|--------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Q1-1   | 58.627            | 281.55            | 222.36            | 1.27             | 1.53             | 1.84             | 153.38            | 1.84             |
| Q1-2   | 58.627            | 279.48            | 222.36            | 1.26             | 1.51             | 1.82             | 153.38            | 1.82             |
| Q2-1   | 58.627            | 260.44            | 222.36            | 1.17             | 1.41             | 1.70             | 153.38            | 1.70             |
| Q2-2   | 58.627            | 264.94            | 222.36            | 1.19             | 1.44             | 1.73             | 153.38            | 1.73             |
| Q3-1   | 58.627            | 203.04            | 222.36            | 0.91             | 1.10             | 1.32             | 153.38            | 1.32             |
| Q3-2   | 58.627            | 193.71            | 222.36            | 0.87             | 1.05             | 1.26             | 153.38            | 1.26             |
| Average|                   |                   |                   | 1.11             | 1.34             | 1.61             |                   |                   |
| Variance|                  |                   |                   | 0.16             | 0.19             | 0.23             |                   |                   |

It can be seen from Table 3 that the ratios of the measured value of the test ultimate shear load to the calculated value of formula (1) are 1.27, 1.26, 1.17, 1.19, 0.91, 0.87, the ratios of the measured value of the test ultimate shear load to the calculated value of formula (2) are 1.53, 1.51, 1.41, 1.44, 1.10, 1.05.
the ratios of the measured value of the test ultimate shear load to the calculated value of formula (3) are 1.84, 1.82, 1.70, 1.73, 1.32, 1.26. It is shown that the formula (1) overestimates the shear capacity of the specimens of epoxied joints with single keys with 20% defects in the cemented surfaces, and the formula (1) underestimates the shear capacity of the specimens with no defects and the specimens with 10% defects, formulas (2) to (3) underestimate the shear capacity of these three specimens. The average values of the ratios of the measured values of the test ultimate shear load to the calculated values of formulas (1) to (3) are 1.11, 1.34, 1.61, and the variances are 0.16, 0.19, 0.23. It shows that formula (1) has the best effect on predicting the shear capacity of the epoxied joints with single keys, and the ratio of the measured value of the ultimate shear load to the calculated value of formula (1) has the smallest fluctuation.

5. Conclusions
By studying the defect degree of cemented surface on the shear behaviour of prefabricated segmented epoxied joints, the following conclusions are drawn:

1) Compared with the specimens with 10% defects and the specimens with 20% defects, the shear capacity, normalized shear stress and plastic deformation capacity of the specimens of epoxied joints with single keys without defect in the cemented surfaces have been improved.

2) The BUYUKOZTURK O formula overestimates the shear capacity of the specimens of epoxied joints with single keys with 20% defects in the cemented surfaces, and the BUYUKOZTURK O formula underestimates the shear capacity of the specimens with no defects and 10% defects, Sun Xueshuai formula and Yuan Aimin formula underestimate the shear capacity of these three specimens. The BUYUKOZTURK O formula has the best effect on predicting the shear capacity of the epoxied joints with single keys.

3) The calculation formulas of the shear capacity of the epoxied joints with single keys proposed by most scholars generally do not take into account the factor of the defect degree in cemented surfaces, so the calculation formulas of the shear capacity of the epoxied joints with single keys have a certain scope of application, which will be further developed in the subsequent work.

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