Experimental Study on Shear Behavior of Fiber Reinforced Concrete Beams with Corroded Stirrups

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Abstract. Through orthogonal test design, the influence factors of shear behavior of fiber reinforced concrete beams under different stirrup corrosion levels are studied. Three factors water cement ratio (A), fiber type (B) and fiber content (C) are determined, each factor contains three levels. 27 reinforced concrete beams of equal height and width with 3 corrosion levels were designed and subjected to continuous loading test after accelerated corrosion by electrification. According to the test results, the influence curve of each influencing factor on the test index is drawn, and the influence order of each influencing factor on the test index is determined according to the range analysis method.

Keyword. Stirrup corrosion, fiber reinforced concrete, shear capacity, orthogonal test.

1. Introduction

Reinforced concrete structure has the advantages of convenient construction and easy access to materials. It is widely used in building materials. However, due to the bad service conditions such as marine environment and industrial environment, environmental pollution caused by the increase of carbon dioxide concentration and acid rain, steel corrosion in concrete structure has become a common phenomenon, the safety and durability of the structure have been seriously affected.

In recent years, experts at home and abroad have done a lot of research on the shear capacity of the inclined section of corroded reinforced concrete beams. Xu [1] and Niu [2] carried out an experimental study on the shear behavior of 18 corroded reinforced concrete beams and 3 corrosion-free contrast beams. The results show that the stirrup corrosion reduces the bond behavior between stirrups and concrete; stirrup corrosion greatly affects the shear strength of corroded reinforced concrete beams; the failure mode of test beams is determined by shear span ratio, concrete strength and stirrup corrosion only affect the shear capacity of test beams. Xiong et al. [3] found that the corrosion level of stirrups has little effect on the shear behavior of beams when the corrosion level of stirrups is less than 5% and the ultimate shear capacity of beams decreases significantly with the increase of corrosion level. Zhao et al. [4] hold that the shear capacity of the test beam decreases significantly with the increase of the corrosion level when the corrosion level of stirrups is greater than 10%.

Fiber can greatly limit the development of concrete cracks [5], so as to significantly improve the splitting tensile, flexural and shear strength of concrete, it can just make up for the shortcomings of the mechanical properties of concrete when the fiber is added into the concrete. Orthogonal test is a method to determine the influence factors of a certain target value by mathematical method. The orthogonal test on the shear performance of small concrete specimens after corrosion has been
reported in the literature. Guo [6] studied the shear behavior of steel fiber reinforced concrete, and the results show that the fiber content is the most influential factor. However, the orthogonal test on the shear capacity of corroded concrete beams, columns and slabs has not been reported yet. In this paper, the influence factors of shear capacity of fiber reinforced concrete beams with corroded stirrups are studied.

2. Experimental Methods

2.1. Materials and Mixture Proportions

The raw materials used for pouring concrete are the same. The cement is P·II42.5R conch Portland cement, and the water is tap water, some properties of cement provided by the manufacturer are shown in table 1, the river sand is medium sand and its properties are shown in table 2, continuous Graded Macadam with nominal size of 5~31.5 mm is used in the test and the correlation is shown in table 3. HRB400 grade hot rolled ribbed bar with diameter of 18mm is used for longitudinal tensile reinforcement. HPB300 round reinforcement with diameter of 6mm is adopted for stirrup and frame reinforcement. The performance index of reinforcement is shown in table 4. The physical and mechanical parameters of three fibers are shown in table 5.

| Table 1. Properties of cement. |
|--------------------------------|
| Specific surface area | Initial setting time | Final setting time | Stability |
| 403 cm²/g | 115 min | 190 min | qualified |

| Table 2. Properties of Sand. |
|------------------------------|
| Fineness modulus | Apparent density | Bulk density | Particle size distribution |
| 2.69 | 2663 kg/m³ | 1365 kg/m³ | II |

| Table 3. Properties of coarse aggregate. |
|----------------------------------------|
| Apparent density | Bulk density | Water absorption | Crushing value |
| 2802 kg/m³ | 1404 kg/m³ | 1.3% | 12.4% |

| Table 4. Mechanical properties of reinforcement. |
|-----------------------------------------------|
| Strength grade | Nominal diameter | Yield strength | Tensile strength | Elastic modulus |
| HPB300 | 6 mm | 467 MPa | 588 MPa | 2.1×10⁵ MPa |
| HRB400 | 18 mm | 489 MPa | 645 MPa | 2.0×10⁵ MPa |

| Table 5. Fiber physical index. |
|-------------------------------|
| Name | Density | Tensile strength | Elastic modulus | Ultimate elongation | Diameter |
| Carbon fiber | 1.76 g/cm³ | 3800 MPa | 230 GPa | 1% | 7 μm |
| Glass fiber | 2.7 g/cm³ | 1700 MPa | 7.0~8.0 GPa | 2.0~3.5% | 14 μm |
| Polypropylene fiber | 0.96 g/cm³ | ≥500 MPa | ≥3.85 GPa | 10~28% | 18~48 μm |

A large number of experiments have proved that "orthogonal test method" is a more effective mathematical method for arranging multi factor test problems which selecting representative test points in a large number of experiments and arranging experiments by orthogonal table by using the viewpoint of mathematical statistics and applying the principle of orthogonality [7]. In this paper, the water cement ratio, fiber type and fiber content are taken as three factors, each factor taking three
levels. L₉(3³) orthogonal test table is selected to arrange the test, the factor level table is shown in table 6, and the fiber content is calculated according to the volume ratio. The test indexes are inclined section cracking load \( V_1 \) and ultimate shear capacity \( V_{max} \). The concrete mixture proportion is shown in table 7.

Table 6. Orthogonal factor.

| Level | Water cement ratio (A) | Fiber type (B) | Fiber content (C) |
|-------|------------------------|----------------|------------------|
| 1     | 0.47                   | Carbon fiber   | 0.5%             |
| 2     | 0.52                   | Glass fiber    | 0.8%             |
| 3     | 0.57                   | Polypropylene fiber | 1%              |

Table 7. Mixture proportion.

| Combination mode | Material consumption (kg/m³) |
|------------------|-----------------------------|
|                  | Water | Cement | Sand | Coarse aggregate | Fiber |
| A1B1C1           | 195   | 414.89 | 587.48 | 1175.38 | 39 |
| A1B2C2           | 195   | 414.89 | 587.48 | 1175.38 | 62.4 |
| A1B3C3           | 195   | 414.89 | 587.48 | 1175.38 | 78 |
| A2B1C2           | 195   | 372    | 595.2  | 1190.40 | 62.4 |
| A2B2C3           | 195   | 372    | 595.2  | 1190.40 | 78 |
| A2B3C1           | 195   | 372    | 595.2  | 1190.40 | 39 |
| A3B1C3           | 195   | 342.11 | 617.85 | 1236.04 | 78 |
| A3B2C1           | 195   | 342.11 | 617.85 | 1236.04 | 39 |
| A3B3C2           | 195   | 342.11 | 617.85 | 1236.04 | 62.4 |

2.2. Casting and Curing of Concrete Beams

A total of 27 concrete beams with the same reinforcement ratio and the same concrete compressive strength were designed in 9 groups with 3 stirrups corrosion level in each group. The concrete strength used in the test is C30. Referring to the existing test beam template and loading device in the laboratory, the size of the concrete beam is taken as 120 mm × 200 mm × 1500 mm. The specific size and detailed reinforcement of the concrete beam are shown in figure 1.

Figure 1. Details of beam.

2.3. Accelerated Corrosion of Rebars

In this test, only the stirrup is corroded, so the insulating tape is used to isolate the stirrup from the longitudinal reinforcement when binding the reinforcement cage, so as to only electrify the stirrup. The method of welding one electrified steel bar on the stirrup is adopted for energizing.

Three corrosion levels of 0%, 5% and 10% were designed. In order to achieve the ideal corrosion level of stirrups in a short time, the electrochemical method was used to accelerate the corrosion of reinforcement in the beam. The specific methods are as follows: after 28 days of curing the beam, immerse it in 5% NaCl solution, and after it is fully moistened, connect the wire connecting the stirrup with the anode of constant voltage and constant current source, and connect the cathode with the
stainless-steel bar immersed in the solution, and form a loop through the NaCl solution to make the reinforcement of the anode corroded, as shown in figure 2.

According to Faraday's law of electromagnetism, the corrosion degree of steel bar is related to the time of electrifying and the magnitude of current. In order to make the result of accelerated corrosion close to the actual situation, the corrosion current of 1 mA/cm² is selected in the test. The power on time of the beam under three corrosion levels is calculated, as shown in table 8.

| Table 8. Electrifying time of corrosion. |
|-----------------------------------------|
| Target corrosion level | 0%  | 5%  | 10% |
| Electrifying time/h     | 0   | 48.55 | 97.1 |

2.4. Loading Experiment of Beams
The test is a static load test of simply supported beam. The supporting length at both ends is 150 mm, the calculation span is 1200 mm, and the pure bending length is 400 mm. The loading force is applied to two symmetrical points on the test beam through the distribution beam, and the steel plate is used to level the surface of the test beam and the support to ensure uniform loading.

3. Results and Discussion

3.1. Experimental Phenomena
The loading process of the beam with 0% corrosion level in group 1 is taken as an example to illustrate the shear test of the beam. During the loading process, when the load reaches 70.3 kN, the vertical bending cracks appear in the middle of the beam; when the load reaches the inclined section cracking load \( V_1 \), i.e. 94.12 kN, the inclined cracks appear at both ends of the beam; when the load continues to increase to 105.6 kN, the diagonal cracks bifurcate; when the load reaches 122.1 kN, the stirrups intersecting with the diagonal cracks reach yield; when the load continues to load to \( V_{\text{max}} \), the shear compression failure occurs at the maximum inclined crack, and the concrete has no obvious crushing phenomenon. The failure mode and crack of the beam are shown in figure 3.
It can be seen that the fourth group has the highest shear capacity and inclined crack cracking load, that is, the optimal combination is A2B1C2.

### Table 9. Loading test results.

| Combination mode | Corrosion level 0% | Corrosion level 5% | Corrosion level 10% |
|------------------|--------------------|--------------------|---------------------|
|                  | $V_1$ (kN)        | $V_{\text{max}}$ (kN) | $V_1$ (kN)        | $V_{\text{max}}$ (kN) |
| A1B1C1           | 94.12             | 130.1              | 80.44              | 114.5               | 66.67              | 98.8               |
| A1B2C2           | 92.81             | 128.6              | 75.96              | 109.4               | 65.96              | 98.0               |
| A1B3C3           | 92.02             | 127.7              | 77.46              | 111.1               | 67.37              | 99.6               |
| A2B1C2           | 100.70            | 137.6              | 85.00              | 119.7               | 70.70              | 103.4              |
| A2B2C3           | 94.56             | 130.6              | 83.33              | 117.8               | 69.74              | 102.3              |
| A2B3C1           | 96.23             | 132.5              | 84.04              | 118.6               | 71.67              | 104.5              |
| A3B1C3           | 88.16             | 123.3              | 72.72              | 105.7               | 61.84              | 93.3               |
| A3B2C1           | 89.04             | 124.3              | 76.67              | 110.2               | 62.28              | 93.8               |
| A3B3C2           | 87.72             | 122.8              | 75.00              | 108.3               | 62.54              | 94.1               |

### 3.3. Range Analysis

Orthogonal test is a scientific test method summed up on the basis of a large number of practices, which adopts the design principles of balanced dispersion and orderly comparability to reasonably arrange the test [8]. The influence of each factor on the test index is determined by the range analysis method of data. The calculation is shown in table 10.

### Table 10. Range calculation of $V_1$ and $V_{\text{max}}$.

| Corrosion Level | Calculation items | Factor |
|-----------------|-------------------|--------|
| 0%              | K1                | A2     |
|                 |                   | B1     |
|                 |                   | C2     |
| 0%              | K2                | 278.95 |
|                 |                   | 282.98 |
|                 |                   | 279.39 |
| 0%              | K3                | 291.49 |
|                 |                   | 276.41 |
|                 |                   | 281.23 |
| 0%              | R1                | 264.92 |
|                 |                   | 275.97 |
|                 |                   | 274.74 |
| 0%              | Excellent level   | 97.16  |
|                 |                   | 94.33  |
|                 |                   | 93.74  |
| 5%              | K1                | 200.00 |
|                 |                   | 199.21 |
|                 |                   | 200.62 |
| 5%              | K2                | 233.86 |
|                 |                   | 238.16 |
|                 |                   | 241.15 |
| 5%              | K3                | 252.37 |
|                 |                   | 235.96 |
|                 |                   | 235.96 |
| 5%              | R2                | 224.39 |
|                 |                   | 236.50 |
|                 |                   | 233.51 |
| 5%              | Excellent level   | 84.12  |
|                 |                   | 79.39  |
|                 |                   | 80.38  |
| 10%             | K1                | 212.11 |
|                 |                   | 197.98 |
|                 |                   | 199.20 |
| 10%             | K2                | 186.66 |
|                 |                   | 201.58 |
|                 |                   | 198.95 |
| 10%             | K3                | 70.70  |
|                 |                   | 67.19  |
|                 |                   | 66.87  |
| 10%             | Excellent level   | A2     |
|                 |                   | B3     |
|                 |                   | C1     |

It can be seen from table 10 that the range values of various factors under different corrosion levels are very small and the range values of water cement ratio are the largest under different corrosion levels, which shows the water cement ratio is most important factor affecting shear behavior of beams. The relationship between factors and $V_{\text{max}}$ under different levels is shown in figure 4.
Figure 4. Relationship between factors and ultimate shear capacity $V_{\text{max}}$ under different levels.

Some results can be seen from the table 10 and figure 4: (1) When the corrosion level is 0% and 10%, the order of influencing factors on ultimate shear capacity and diagonal crack cracking load is water cement ratio > fiber type > fiber content; (2) When the corrosion level is 5%, the order of influencing the cracking load of concrete beams is water cement ratio > fiber content > fiber type; (3) The water cement ratio $a$ is the main factor affecting the shear behavior of concrete beams, while the fiber type and fiber content have little influence on the shear behavior of concrete beams.

3.4. Relationship between Shear Behavior Index and Stirrup Corrosion Level
After the test, the beam is broken, and the actual corrosion level is measured by cutting off the corroded stirrups. The actual corrosion level is shown in table 11.

| Combination mode | Target corrosion level (%) |
|------------------|---------------------------|
|                  | 0 | 5 | 10 |
| A1B1C1           | 0.20 | 5.3 | 11.3 |
| A1B2C2           | 0.43 | 4.6 | 10.4 |
| A1B3C3           | 0.15 | 5.0 | 9.7 |
| A2B1C2           | 0.25 | 5.7 | 10.1 |
| A2B2C3           | 0.32 | 4.9 | 9.0 |
| A2B3C1           | 0.30 | 5.2 | 9.5 |
| A3B1C3           | 0.22 | 4.4 | 10.4 |
| A3B2C1           | 0.58 | 5.8 | 10.8 |
| A3B3C2           | 0.16 | 4.2 | 9.7 |

The relationship between $V_{\text{max}}$ and stirrup corrosion level is drawn based on the condition of water cement ratio, which is the biggest influencing factor, as shown in figure 5. It can be seen from figure 5 that under the same water cement ratio, with the increase of stirrup corrosion level, the shear capacity of the beam shows a downward trend, which is consistent with the existing research results.
4. Conclusions
In this paper, through the loading test of beams with corroded stirrups and the principle of orthogonality, the following conclusions are obtained.

(1) When the corrosion level is 0% and 10%, the order of influencing factors on ultimate shear capacity and diagonal crack cracking load is water cement ratio>fiber type>fiber content.

(2) When the corrosion level is 5%, the order of influencing the cracking load of concrete beams is water cement ratio>fiber content>fiber type.

(3) The water cement ratio a is the main factor affecting the shear behavior of concrete beams, while the fiber type and fiber content have little influence on the shear behavior of concrete beams.

(4) Under the same water cement ratio, with the increase of stirrup corrosion level, the shear capacity of the beam shows a downward trend.

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