Experimental Study on Crack Characteristics of Damaged Reinforced Concrete Beams strengthened with CFRP

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Abstract: The bending tests of 2 control beams and 6 damaged beams strengthened with CFRP (DBSC) were carried out to study the effects of adhesive layer thickness, number of CFRP layers and reinforcement ratio on crack characteristics of DBSC. The test results show that the crack development of the DBSC is accelerated and the crack resistance of the DBSC is reduced compared with the intact beam. With the increase of the thickness of the adhesive layer, the crack development of the DBSC is slowed down and the crack resistance is improved. Increasing the number of CFRP layers is helpful to restrain the crack development of DBSC under high load level. The increase of reinforcement ratio can significantly improve the crack resistance of DBSC.

1. Introduction

Bridge is an important part of modern traffic network. A large number of existing bridges have been working with diseases for a long time due to low engineering technical standards during construction, inadequate management and maintenance during operation, and imminent expiry of design service life. The hidden danger of safety cannot be ignored, and the huge economic and social costs of complete demolition and reconstruction are unbearable. How to solve the problem to ensure the safety and reliability of existing bridges has become a major practical demand of China and even the world[1].

Fiber Reinforced Polymer (FRP) has been widely used in the reinforcement of existing bridges because of its advantages such as light weight, corrosion resistance, high strength and convenient construction. For CFRP reinforced beams, the development of cracks will not only reduce the overall stiffness and durability of the structure, but also affect the bonding performance of CFRP-concrete interface. Ceroni[2] found that concrete strength, reinforcement ratio and CFRP layer number would have an impact on the bonding performance of the reinforced members by single shear test. Ueda[3] conducted double shear test and found that with the increase of the CFRP amount, the average stress of concrete specimens decreased, and the average and maximum spacing of cracks both decreased. Sebastian[4] found that the peeling failure of the bond interface in the middle of the reinforced beam was caused by the high shear stress of FRP transferred to the concrete through the bond adhesive. Smith[5] and Lu[6] described the interface stripping failure process through the bond-slip relationship between FRP and concrete interface. Gong[7] found that the crack load of the reinforced beam was less affected
by FRP, and FRP inhibited the crack development of the reinforced beam. The crack width and spacing of the reinforced beam were smaller than the corresponding the unreinforced beam. Liu[8], Tan[9] and Zhuang[10] respectively deduced the formula for calculating crack width of reinforced beams. Cao[11] established a crack analysis model of the reinforced beam based on bond-slip theory. Lin[12] established an analytical model to study the bond slip of CFRP-concrete interface between adjacent cracks.

These studies promote the application and development of FRP in the field of RC beam reinforcement, but the research objects are mostly intact RC beams reinforced by FRP. In order to accord with actual structure, this paper takes damaged beam as the object to study the influence of adhesive layer thickness, reinforcement amount and reinforcement ratio on the crack characteristics of damaged beams strengthened with CFRP (DBSC).

2. Experimental program

2.1. mechanical properties of materials

Standard cube specimen and standard prism were poured with the same batch of concrete poured into the test beam, and were cured synchronously with the test beam for 28d. Based on the measured data, the standard value of concrete’s compressive strength is 39.6MPa, the standard value of axial tensile strength is 2.49MPa, and the elastic modulus is $2.72 \times 10^5$ MPa. The mechanical property parameters of the steel bars are calculated according to Code for Design of Concrete Structures (GB 50010-2010). Toray UT70-30 CFRP and Sikadur 330CN two-component epoxy carbon cloth impregnated adhesive are used. The mechanical properties of the materials are shown in Table 1.

| materials | Mechanical properties | Values |
|-----------|-----------------------|--------|
| CFRP      | effective thickness (mm) | 0.167  |
|           | tensile strength (MPa) | 3896   |
|           | elasticity modulus (MPa) | $2.39 \times 10^5$ |
|           | ultimate tensile strain | 0.0173 |
| Adhesive  | tensile strength (MPa) | 49.8   |
|           | elasticity modulus (MPa) | 2550   |
|           | elongation | 0.0184 |
|           | flexure strength (MPa) | 79.4   |
|           | Tensile bond strength (MPa) | 3.23 |

2.2. Test specimens

The specimens were simply supported beams. Each specimens was 200×120×2300mm and the calculated span was 2100 mm. The longitudinal bars of the test beams were HRB335 steel bars (N1) with diameters of 10 mm, 12 mm, 14 mm, respectively. The vertical reinforcement (N2) and stirrup (N3) were made of HPB235 steel bars with a diameter of 6 mm. The space between stirrups in pure bending section was 160 mm, and the space between stirrups in bending and shearing section was 100 mm. The CFRP with the length of 1900 mm and width of 80 mm were pasted on the bottom of the specimens. The specimens and CFRP are shown in Figure 1.

![Figure 1. Geometry and reinforcing details of test beams (unit: mm)](image-url)
A total of 8 RC beams were designed in the test. DB-1 was an un-reinforced RC beam. DB-2 was a RC beam strengthened with CFRP. JG-1 to JG-6 were damaged RC beams strengthened with CFRP (DBSC). JG-1 to JG-3 took the thickness of the adhesive layer as the variable. JG-4 increased the number of CFRP layers. JG-5 and JG-6 changed the reinforcement ratio of the test beam.

The damage degree of the test beam is quantified by the damage coefficient, which is the ratio of the pre-crack load to the ultimate load of the unreinforced reference beam (DB-1). The measured ultimate load of DB-1 is 48.1 kN, and the damage coefficient of experimental design is 0.3, so the pre-cracking load of JG-1 to JG-4 is 14.4 kN. Since there is no measured data of unreinforced reference beam with corresponding reinforcement ratio, the pre-cracking loads of JG-5 and JG-6 are obtained by multiplying the ultimate loads calculated by the finite element model and the damage coefficient 0.3, which are 11.3 kN and 18.1 kN, respectively. The design parameters of each specimen are shown in Table 2.

| specimen | Reinforcement ratio(%) | number of CFRP layers | adhesive layer thickness(mm) | damage coefficient |
|----------|------------------------|-----------------------|-----------------------------|-------------------|
| DB-1     | 1.19                   | /                     | /                           | /                 |
| DB-2     | 1.19                   | 1                     | 0.5                         | /                 |
| JG-1     | 1.19                   | 1                     | 1                           | 0.3               |
| JG-2     | 1.19                   | 1                     | 2                           | 0.3               |
| JG-3     | 1.19                   | 1                     | 3                           | 0.3               |
| JG-4     | 1.19                   | 2                     | 1                           | 0.3               |
| JG-5     | 1.63                   | 1                     | 1                           | 0.3               |
| JG-6     | 0.82                   | 1                     | 1                           | 0.3               |

2.3. Test procedures

During the test, the hydraulic jack with the maximum lifting mass of 20 t was used to apply the load. The jack was arranged in the position of the middle line of the distribution beam, and the distance between the two fulcrums of the distribution beam was 700 mm. The load of the test beam was controlled before the yield of the longitudinal bars, and the load of each stage was 2 kN. The mid-span displacement of the test beam was used to control the loading after the yield of the longitudinal bars, and the displacement of each stage was 1 mm. After the completion of loading at each stage, the load was held for 2 min, and the test data were collected after the load and deformation were stabilized. The test loading device is shown in Figure 2.

![Figure 2. Schematic representation of the test system](image)

3. General behavior and mode of failure

When the load reached 9.7 kN, the bottom of DB-1 beam cracked, and three initial cracks appeared near the loading point and mid-span section. With the increase of load, several main cracks appeared successively among the initial cracks. The width and length of each crack developed with the increase of...
load, and the growth of the crack near the loading point and mid-span section developed the fastest. There were few new cracks in this stage and the crack spacing was large. After the longitudinal bars yielded, the new cracks no longer appeared, and the developing speed of the main crack was accelerated. Finally, the crushing of the concrete compression zone marked the end of loading. At this time, the main crack developed to 4/5 of beam height, and there were several penetrating cracks at the bottom of the beam, as shown in Figure 3.

Figure 3. Crack distribution of DB-1

When the loading value researched 10.8 kN, the bottom of DB-2 beam cracked, and initial cracks appeared near the loading point and mid-span section. With the increase of load, several main cracks appeared between the initial cracks. The width and length of each crack developed with the increase of the load. In this stage, more new cracks appeared, and the average width and spacing of cracks were significantly reduced compared with DB-1. There were still small oblique cracks near the main crack after yielding of the longitudinal bars, and the development speed of the main crack was accelerated. Finally, the loading ended with the peeling of CFRP, as shown in Figure 4.

Figure 4. Crack distribution of DB-2

JG-1 to JG-6 were damaged reinforced beams. Before formal loading, pre-cracking load with a damage coefficient of 0.3 was applied to each specimen. The crack development process of JG-1 to JG-6 were generally similar, and the difference was mainly reflected in the crack development rate and final distribution pattern.

In the process of pre-cracking loading, the initial cracks also appeared near the loading point and mid-span section, and then a small number of secondary cracks appeared between the initial cracks. In this stage, the crack spacing was large and the width is small. After the pre-cracking loading was completed, the test beams were unloaded and reinforced. At the initial stage of formal loading, the width and length of the old cracks generated by several pre-cracking loading developed with the increase of load, while the crack spacing decreased with the emergence of new cracks, and the development of cracks was similar to that of DB-2. With the yield of the longitudinal bars, the oblique crack appeared near the section of the loading point. Finally, the loading ended with the peeling of CFRP cloth, as shown in Figure 5.
4. Test results and discussion

The crack morphology of each specimen from the beginning of loading to the yield stage of longitudinal bars is taken as the research object.

4.1. Crack width

The average widths of the main crack in the area near the loading point section of each test beam are taken to draw the load-crack width curve, as shown in Figure 6.

Figure 5. Crack distribution of damaged reinforced beams
The average crack width of DB-2 is significantly smaller than that of DB-1, indicating that CFRP cloth has an inhibitory effect on the crack development of the reinforced beam. The average crack width of DB-2 is less than that of JG-1, indicating that the speed of crack development of the damaged reinforced beam is faster than that of the intact reinforced beam. Compared with JG-1, JG-2 and JG-3, it can be seen that the three curves are very similar before the load reaches 25 kN. Before the yield of longitudinal bars, the larger the thickness of the adhesive layer is, the smaller the average width of cracks will be, indicating that the increase of the thickness of the adhesive layer can slow down the crack development of the reinforced beam. Compared with JG-1 and JG-4, it can be seen that the average crack width of the two curves is close before the load reaches 30 kN. As the load continues to increase, the average crack width of JG-4 is less than that of JG-1, indicating that the growth of thickness of CFRP layers can inhibit the crack development of the reinforced beam under high load level. Compared with JG-1, JG-5 and JG-6, it can be seen that the developments of the three curves are significantly different. The order of the average crack width from large to small is JG-6, JG-1 and JG-5, indicating that the increase of reinforcement ratio has a significant inhibitory effect on the crack development of the reinforced beam.

4.2. Crack characteristic
The crack characteristic of each test beam under typical load are shown in Table 3.

| Specimen | Load (kN) | Average spacing (mm) | Average width (mm) | Maximum width (mm) |
|----------|-----------|----------------------|--------------------|--------------------|
| DB-1     | 36.3      | 95.2                 | 0.22               | 0.32               |
| DB-2     | 41.8      | 77.3                 | 0.15               | 0.25               |
| JG-1     | 41.8      | 84.7                 | 0.19               | 0.29               |
| JG-2     | 42.6      | 82.4                 | 0.17               | 0.27               |
| JG-3     | 43.5      | 81.2                 | 0.16               | 0.28               |
| JG-4     | 45.3      | 78.6                 | 0.17               | 0.25               |
| JG-5     | 48.0      | 82.1                 | 0.16               | 0.26               |
| JG-6     | 36.5      | 85.4                 | 0.22               | 0.34               |
Compared with DB-1, the average crack spacing, average crack width and maximum crack width of DB-2 are significantly reduced, indicating that the crack resistance of the reinforced beam is improved. The average crack spacing, average crack width and maximum crack width of DB-2 are all smaller than that of JG-1, indicating that the crack resistance of the DBSC decreases compared with that of the intact strengthened beam. Compared with JG-1, JG-2 and JG-3, it can be seen that the average crack spacing and average crack width of the reinforced beam decrease with the increase of the thickness of the adhesive layer, indicating that the increase of the thickness of the adhesive layer can enhance the crack resistance of the reinforced beam. The yield load of JG-4 is larger than that of JG-1, and the average crack spacing and average crack width are smaller, indicating that the increase of the number of CFRP layers can improve the crack resistance of the strengthened beam. Compared with JG-1, JG-5 and JG-6, it can be seen that the average spacing, average width and maximum width of cracks of the strengthened beams decrease with the increase of reinforcement ratio, indicating that the increase of reinforcement ratio can significantly improve the crack resistance of the strengthened beams.

5. Conclusion
The bending tests of 2 control beams and 6 DBSC were carried out to study the effects of adhesive layer thickness, number of CFRP layers and reinforcement ratio on crack characteristics of DBSC. The following conclusion can be drawn.

1. Compared with the intact beams, the growth speed of cracks of DBSC is accelerated and the crack resistance of the damaged beams is reduced.
2. With the increase of the thickness of the adhesive layer, the crack development of the DBSC slows down, and the average spacing and width of the crack decrease.
3. Increasing the number of CFRP layers has little effect on the crack resistance of the beams under low load, but it is helpful to restrain the crack development of the beams under high load.
4. The increase of reinforcement ratio can obviously delay the crack development and enhance the crack resistance of the reinforced beam.

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