Experimental Study on Shear Behavior of Reactive Powder Concrete Beam

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Abstract. In order to study the shear behavior of high-strength reinforced Reactive Powder Concrete (RPC) beams, eight test beams were designed and fabricated for the shear test under symmetrical concentrated load. By observing the development and failure mode of diagonal cracks, the influence of shear span ratio, stirrup ratio, and longitudinal reinforcement ratio on the cracking load, shear capacity, and deflection of the test beam is analyzed. The results show that: in a specific range, the shear capacity increases with the increase of stirrup ratio and longitudinal reinforcement ratio and decreases with the increase of shear span ratio. The shear span ratio has the most significant influence on the component's failure mode and deformation capacity. The increase of the stirrup ratio can improve the deformation capacity of the component in a specific range. It is conservative to use the code to design concrete structures to calculate the shear capacity of high-strength reinforced reactive powder concrete beams. It is suggested that the shear calculation formula suitable for high-strength reinforced reactive powder concrete should be adopted to make the theoretical calculation results closer to the measured values.

1. Introduction

With the development of society, ordinary concrete cannot meet the needs of some engineering construction due to the lack of strength and durability. Reactive Powder Concrete (RPC) is a high-performance concrete with long-term stable mechanical properties [1], high early strength, high toughness, good volume stability, and long service life under adverse conditions. It is the development direction of building concrete materials [2]. HRB500 steel bar is a kind of steel bar with high strength and good ductility. In recent years, there have been some researches on the shear behavior of high-strength reinforced RPC members at home and abroad. Through a series of shear tests of prestressed RPC beams without web reinforcement, Australian scholars Vool and Foster [3] summarized the effects of prestressing size, steel fiber type, and steel fiber content on shear capacity. Based on the softened truss theory model, Cladera [4] proposed a shear model and shear formula considering the contribution of tensile strength to concrete shear capacity. Zheng Hui [5] carried out the load test of prestressed RPC thin-walled box girder, summarized the influence of stirrup ratio, shear span ratio, and other parameters on the components, and put forward that the tensile strength of RPC can be improved by adding 2% steel fiber in volume, and the cracks in the test beam present the characteristics of "fine and dense".
2. General Situation

2.1. Design and Manufacture of Specimen

Eight RPC rectangular beams with high-strength steel bars are designed, and their section sizes are all $B \times h=150\text{mm} \times 250\text{mm}$, beam length is 2200mm. The parameters of each test beam are shown in Table 1.

| Specimen number | Volume fraction of steel fiber | Shear span ratio $\lambda$ | Stirrup $\sigma$ | Stirrup ratio % | Longitudinal reinforcement | Longitudinal reinforcement ratio % |
|----------------|-------------------------------|-----------------------------|-----------------|-----------------|---------------------------|-----------------------------------|
| L1-1           | 2%                            | 1.51                        | C6@450          | $\approx 0$     | 4D25                      | 6.58                              |
| L1-2           | 2%                            | 2.26                        | C6@450          | $\approx 0$     | 4D25                      | 6.58                              |
| L1-3           | 2%                            | 3.02                        | C6@450          | $\approx 0$     | 4D25                      | 6.58                              |
| L2-1           | 2%                            | 2.26                        | C6@450          | $\approx 0$     | 3D25                      | 4.43                              |
| L2-2           | 2%                            | 2.26                        | C6@450          | $\approx 0$     | 5D25                      | 8.04                              |
| L3-1           | 2%                            | 2.26                        | C6@225          | 0.17            | 4D25                      | 6.58                              |
| L3-2           | 2%                            | 2.26                        | C6@150          | 0.25            | 4D25                      | 6.58                              |
| L3-3           | 2%                            | 2.26                        | C6@65           | 0.58            | 4D25                      | 6.58                              |

2.2. Loading Mode and Measurement Scheme

The static loading method is adopted in this test, and two equivalent and synchronous concentrated forces are obtained by distributing the symmetrical position of the steel beam on the test beam. The measurement contents include deflection, steel strain, crack, and load. See figure 1 for details.

Figure 1. Loading device diagram.

3. Test Results and Analysis

3.1. Experimental Phenomena

The failure characteristics of RPC beams are similar to those of ordinary beams. When the load is small, the tensile strength of RPC mainly resists the shear force, and there is no crack on the concrete surface. When the load is about 200kN, small shear cracks appear at the bottom of the beam in the shear span area. With the increase of the load, the cracks develop into bending inclined cracks. With the continuous increase of load, the inclined crack extends along the beam height direction, the crack width increases, and new inclined cracks appear at the same time. Finally, the bearing capacity of the beam decreased rapidly due to the concrete being pressed and peeled off.
3.2. Failure Mode
Adding an appropriate amount of steel fiber into RPC can improve the failure characteristics of RPC, bridge cracks and hinder the development of cracks. The failure forms of RPC inclined section of high-strength reinforcement are mainly divided into shear compression failure, oblique compression failure, and bending shear failure, as shown in figure 2 to figure 4.

- Shear compression failure. It can be seen from Figure 2 that the shear compression failure of beams without web reinforcement is L1-2, L1-3, L2-1, L2-2, and beams with web reinforcement L3-1, L3-2, L3-3. During the loading process, the bending cracks first appear in the middle of the test beam span, then the inclined cracks appear in the shear span area, and finally, the inclined cracks are destroyed due to the excessive width of the inclined cracks. In the beam with web reinforcement, when entering the descending section, the stirrups yield, but the longitudinal bars do not yield, and the concrete in the compression area is crushed, which declares that the whole beam loses its bearing capacity and is damaged.

- Baroclinic failure. In this test, the shear span ratio of L1-1 is 1.51, and there are many small cracks in the concrete between the inclined cracks in the abdomen of the test beam, showing a certain characteristic of oblique compression failure, as shown in figure 3.

- Bending shear failure. Because L3-3 is equipped with more stirrups, bending shear failure occurs, not only part of the stirrups yield but also the longitudinal bars near the loading point in the shear span region yield. When the test beam is about to fail, the load is basically unchanged, and the beam deflection continues to increase significantly, showing the characteristics of bending failure, as shown in figure 4.

3.3. Bearing Capacity Analysis
It can be seen from figure 5 that the shear bearing capacity decreases with the increase of shear span ratio. It can be seen from Figure 6 that longitudinal reinforcement can effectively control the width and height of bending cracks, increase the area of concrete contributing to shear resistance, and thus improve the shear bearing capacity, which is called the pin bolt effect of longitudinal reinforcement. The higher the ratio of longitudinal reinforcement is, the greater the pin bolt effect is, and the higher the shear bearing capacity is. It can be seen from Figure 7 that the shear capacity of the inclined section increases with the increase of stirrup ratio, but beyond a certain range, the increase is not obvious. L3-3 has a high stirrup ratio, but the bearing capacity of the inclined section decreases...
slightly. This is due to the shear failure and bending failure. The stirrups yield individually, and the longitudinal bars yield, which leads to the reduction of the bearing capacity of the beam.

**Figure 5.** The curve of shear span ratio and bearing capacity.

**Figure 6.** The curve of reinforcement ratio and bearing capacity.

**Figure 7.** The curve of stirrup ratio and bearing capacity.

**Figure 8.** The curve of shear span ratio on load – deflection.

4. Deformation Behavior of Test Beam

4.1. Deformation Law of Test Beam

It can be seen from figure 8- figure 10 that when the load is relatively small, the load and deformation basically increase in a linear relationship. With the continuous increase of the load, the RPC beam enters the inelastic working stage, and the curve slope slows down, but there is no obvious breakpoint. Near the failure, the deformation increases suddenly. After the failure, the load decreases, the deformation still increases, and the maximum displacement is more than 14mm. This is due to the bridge function of steel fiber in RPC. After the concrete cracks, it effectively prevents the concrete from cracking on the inclined crack surface, and the concrete can still bear part of the force.
4.2. Factors Affecting the Deformation Performance of Test Beams

- Shear span ratio. According to figure 8, the mid-span deformation and deformation speed increase with the increase of shear span ratio. On the one hand, the beam with a large shear span ratio produces a greater bending moment under the same conditions. On the other hand, the beam with a large shear span ratio has smaller stiffness. Therefore, after RPC cracking, the deformation of the beam with a large shear span ratio increases faster, and the deformation will be larger when it reaches failure.

- Longitudinal reinforcement ratio. It can be seen from figure 9 that the longitudinal reinforcement ratio is within a certain range, and the deformation of the RPC beam increases with the increase of longitudinal reinforcement ratio, but the improvement effect is not obvious when the longitudinal reinforcement ratio is too high.

- Stirrup ratio. It can be seen from figure 10 that although the high stirrup ratio restricts the development of oblique cracks, it has no obvious effect on the stiffness of the test beam. Therefore, the development trend of the load midspan deflection curve of the RPC beam is basically the same. In the later stage of loading, the deflection curve of the RPC beam with stirrups did not drop suddenly because the stirrups yielded successively in the load falling section. In particular, the curve of L3-3 is near the ultimate load, the load increases little or basically does not increase, but the deflection increases continuously, which is similar to the characteristics of bending shear failure of beams.

5. Shear Calculation Formula of RPC Beam

In this paper, the shear capacity of the oblique section of the RPC beam adopts the literature[6]:

\[ V_u = \frac{2.5}{\lambda + 1} \sqrt{0.8 f_c \times 5.4 \sqrt{\rho bh_0} + 1.25 f_yv A_{sv} h_b} \]  \hspace{1cm} (1)

In formula (1), \( V_u \) is the shear capacity of the beam, \( \lambda \) is the shear span ratio, \( f_c \) is the compressive strength of concrete, \( \rho \) is the reinforcement ratio of longitudinal reinforcement, \( b \) is the width of concrete section, \( h_0 \) is the effective height of concrete section, \( f_yv \) is the tensile strength of stirrup, \( A_{sv} \) is the stirrup area, and \( s \) is the stirrup spacing.

**Figure 9.** The curve of reinforcement ratio on load – deflection.

**Figure 10.** The curve of stirrup ratio on load – deflection.
Table 2. RPC recommended formula calculation value and experimental value.

| Specimen number | Shear span ratio/λ | Stirrup ratio/% | Reinforcement ratio/% | $f_c$ /N/mm$^2$ | $h_o$ /mm | $V_{cal}$ /kN | $V_{exp}$ /kN | $V_{cal}/V_{exp}$ |
|-----------------|--------------------|-----------------|-----------------------|----------------|-----------|--------------|--------------|-----------------|
| L1-1            | 1.51               | 0               | 6.58                  | 117.2          | 205       | 410.80       | 656          | 0.626           |
| L1-2            | 2.26               | 0               | 6.58                  | 117.2          | 205       | 316.29       | 356          | 0.888           |
| L1-3            | 3.02               | 0               | 6.58                  | 117.2          | 205       | 256.49       | 335          | 0.766           |
| L2-1            | 2.26               | 0               | 4.43                  | 117.2          | 221.5     | 280.41       | 300.5        | 0.933           |
| L2-2            | 2.26               | 0               | 8.04                  | 117.2          | 199       | 339.39       | 425          | 0.799           |
| L3-1            | 2.26               | 0.17            | 6.58                  | 117.2          | 205       | 357.57       | 419.25       | 0.853           |
| L3-2            | 2.26               | 0.25            | 6.58                  | 117.2          | 205       | 378.20       | 430.85       | 0.878           |
| L3-3            | 2.26               | 0.58            | 6.58                  | 117.2          | 205       | 459.17       | 426.25       | 1.077           |

|              | Mean value         | 0.852          |                       |                |           |              |              | 0.123          |
|              | Standard deviation | 0.123          |                       |                |           |              |              | 0.144          |

Through comparison, it can be seen that the average value of the ratio between the calculated value and the test value adopted by the formula is 0.852, the standard deviation is 0.123, and the coefficient of variation is 0.144. The calculated value is close to the measured results, and the shear force of RPC members can be better estimated according to the adopted formula of RPC shear capacity.

6. Conclusion

- The steel fiber added into RPC can improve the failure mode of non-web reinforced beams with a large shear span ratio. With the increase of shear span ratio, the shear capacity of RPC beams decreases, and the deformation accelerates; With the increase of longitudinal reinforcement ratio, the shear capacity and deformation of RPC beams increase, but too high longitudinal reinforcement ratio has no obvious effect on improving the deformation capacity of RPC beams; The shear capacity of RPC beam increases with the increase of stirrup ratio, but the bearing capacity decreases with too many stirrups.
- The shear bearing capacity of high-strength reinforced RPC beams calculated according to the current code for design of concrete structures (gb50010-2010) is quite different from the measured values in the test, but according to the recommended formula of semi-empirical and semi theoretical shear bearing capacity of high-strength reinforced RPC members, the calculated value is close to the theoretical value.

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