Research Article

Research on Deflection of Partial Steel Fiber Reinforced Concrete Beams with BFRP Bars

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1. Introduction

The reinforced concrete structure is a common structure in civil engineering. It is usually used in house construction, bridges, tunnels, and other structures. However, traditional reinforced concrete structures also have many problems of their own, such as self-heavy, poor corrosion resistance, crack resistance. Poor performance and other shortcomings, in places with heavy humidity, it is easy to cause corrosion of steel bars, which reduces the alkalinity of concrete, thus affecting the safety of the structure. Therefore, the deterioration of infrastructure caused by corrosion of steel bars has become one of the main challenges faced by the construction industry, and the use of fiber-reinforced polymer (FRP) bars with good corrosion resistance instead of traditional steel bars can effectively avoid this problem [1–7]. Compared with traditional steel bars, FRP bars can effectively improve the corrosion resistance of the structure, avoid the safety problems of the structure caused by the corrosion of steel bars, and at the same time reduce the self-weight of the structure under the premise of satisfying the structural safety.

However, in the process of use, due to the low elastic modulus of FRP reinforcement, the stress-strain relationship before tensile failure is mainly linear elasticity, and the corresponding yield point is not highlighted, and the stiffness of FRP-reinforced concrete beams decreases significantly after cracking, and at the same time produces larger cracks and deflections affect the applicability of the structure to a certain extent [8–11]. To solve such problems, FRP reinforced concrete beams are combined with steel fibers to form FRP reinforced steel fiber concrete beams, and the reinforcing and toughening effect of steel fibers is used to enhance the force performance of FRP reinforced concrete beams [12–15]. Numerous scholars have conducted studies related to the flexural properties of FRP reinforced steel fiber concrete beams: Issa et al. [16] conducted flexural loading tests on GFRP reinforced concrete beams with differences in concrete strength and fiber type. The addition of FRP can inhibit the deformation of the beam, especially the steel fiber can effectively overcome the problem of low ductility of FRP reinforced concrete beams. Li Jinzhang [17] combined theory and experiment to study the effect of steel fibers on the flexural properties of BFRP reinforced concrete beams.
The mechanical performance has been significantly improved. Cheng Shengzhao [18] focused on the effects of steel fiber volume ratio and reinforcement ratio on the flexural failure form and bearing capacity of FRP reinforced concrete beams. The flexural bearing capacity has been improved to a certain extent. Chen [19] investigated the flexural performance of steel fiber reinforced concrete beams with FRP bars and partial steel fiber reinforced concrete beams with FRP bars for different volume rates of steel fibers. The results showed that the ultimate load carrying capacity of FRP reinforced concrete beams was substantially increased after incorporating steel fibers into the FRP reinforced concrete beams.

However, although the addition of steel fibers can effectively improve the mechanical properties of FRP reinforced concrete beams, there are also obvious deficiencies. The efficiency of steel fibers in the area is limited, and it may also cause safety problems due to insufficient structural durability under long-term action. At present, the research on FRP reinforced concrete beams is focused on the study of single strength, but from the flexural failure mode of FRP reinforced concrete beams, it can be found that the concrete strength in the tensile area, which accounts for a large proportion of the section height, has not been fully exerted [20]. Youcef Fritih [21], Mahir Mahmud [22], and others' studied the effect of adding steel fibers on the flexural properties, splitting tensile strength, and elastic modulus of concrete through experiments, and observed and compared beam ultimate bearing capacity, deflection, crack morphology and failure. The research shows that the flexural performance of the beam increases with the increase of concrete compressive strength, longitudinal reinforcement ratio and fiber content, and the fiber has a certain improvement effect on beam cracks. ISKhakov et al. [23] studied the flexural properties of tensile-compression concrete beams with a higher concrete strength in the compression zone than in the tensile zone. The influence of the moment is not relevant, and the influence on the ultimate bearing capacity is small. Zhou Wei et al. [24] studied the influence of the height of the high-strength concrete layer on the flexural performance of the test beam through the bending test of the concrete beam with different strengths in tension and compression (high-strength concrete in the compression zone and ordinary concrete in the tension zone), and analyzed the effect of the height of the high-strength concrete layer on the bending performance of the beam. The stress and strain distribution law of the normal section of the beam, the research results show that the integrity of the special-strength concrete laminated beam is good, and the calculation formula of the maximum crack and the ultimate bearing capacity of the special-strength concrete laminated beam is established. The addition of fibers to the concrete mix of a flexural member increases the ultimate compressive stress that the concrete can achieve, thereby enhancing the flexural performance of the member. Therefore, it can be considered to add steel fibers only in the compression area of the beam, and use ordinary concrete in the tension area to form a steel fiber reinforced concrete beam part of the FRP bar. The effect of pulling FRP bars together can not only make full use of the strengthening and toughening effect of steel fibers, but also give full play to the characteristics of FRP bars and steel fibers, but also save materials and improve economic benefits.

To sum up, adding steel fibers to the compression zone to enhance the bending performance of beams is a very reliable reinforcement method, and compared with the reinforcement method in which the full section is covered with steel fibers, it has the advantages of low production cost. At the same time, it can not only improve the ultimate compressive strain and ultimate bearing capacity of edge concrete, but also fully display the high toughness characteristics of FRP reinforcement, which reduces the waste of materials to a certain extent, and has the concept of green environmental protection. In this study, basalt fiber reinforced polymer (BFRP) was selected to replace steel reinforcement based on the available research results. The flexural performance of partial steel fiber reinforced concrete beams with BFRP bars was investigated with the steel fiber incorporation rate and the height of steel fibers in the concrete layer in the compression zone as variables. The deflection calculation equation applicable to the partial steel fiber reinforced concrete beam with BFRP bars was also proposed, and the calculation results were compared with the test results to verify the reasonableness of the equation.

2. Trial Overview

2.1. Mix Ratio Design. The raw materials used for the test beam are as follows: the cement is P.042.5 grade ordinary Portland cement; the coarse aggregate is crushed stone with a particle size of 5-20 mm; the fine aggregate is medium-coarse ordinary river sand; water reducer is used; steel fibers are milled and corrugated steel fibers with an aspect ratio of 37. Longitudinal bars are BFRP bars with a diameter of 14 mm, and third-grade threaded bars with a diameter of 8 mm are used for the vertical bars and stirrups. The mechanical properties of BFRP bars are shown in Table 1. The stress-strain curve of the BFRP bar is shown in Figure 1. The parameters of the mix ratio are shown in Table 2.

2.2. Specimen Design. Since the yield strain of FRP reinforcement is very small and will out brittle fracture under larger stress, the test beams were designed as super-reinforced beams. To investigate the effect of the incorporation rate of steel fibers and the height of the steel fiber concrete layer on the deflection of the beam, seven beams with cross-sectional dimensions of 150 mm × 300 mm × 2100 mm were designed with this as a variable.

According to the analyzed literature results, combined with the current research status, and considering the influence of the fiber content and the change of the fiber mixing height in the compression zone of the test beam, this test plan is based on the difference in the position and content of the compression zone. One BFRP reinforced plain concrete beam (B1) and three BFRP reinforced test beams in the compression zone with the upper steel fiber reinforced concrete layer thickness of 180 mm were fabricated (steel
fiber admixture 0.5% (B2), 1.0% (B3), and 1.5% (B4), respectively), a BFRP reinforced test beam (B5) in the compression zone of the upper steel fiber reinforced concrete layer with a thickness of 210 mm (the steel fiber content is 1.0%), and a 1.0% steel fiber content A BFRP reinforced steel fiber reinforced concrete beam (B6), and a BFRP reinforced steel fiber reinforced concrete beam (B7) with a dosage of 1% in the upper part and 0.5% in the lower part. The thickness of the concrete protective layer of each beam is 25 mm, and stirrups are set on both sides of the beam, and no vertical bars and stirrups are set in the middle of the span to avoid affecting the stress of the pure bending section. Those beams are shown in Figure 2.

When the formed specimens were poured, two groups of six standard cube test blocks of 100 mm × 100 mm × 100 mm were made for each beam at the same time, and were jointly cured for 28 d in the same environment to test its compressive strength.

2.3. Test Beam Fabrication. The production process of this test piece is mainly divided into three parts, namely: steel cage production, test piece pouring, and post-maintenance.

(1) Fabrication of steel cages. The production of the reinforcement cage needs to be divided into "three steps", that is, calculating the cutting length, rebar grinding, and reinforcement cage binding. The length of the BFRP bars to be dismantled needs to be determined according to the size and structural requirements of the test beam. According to the test requirements, the BFRP bars are to be straightened, cut, and other processing procedures. The length of this test beam is 2100 mm, the concrete protection layer is 25 mm, the span is not configured with erection bars and hoop reinforcement, the beam is tied with hoop reinforcement on both sides, the selected material diameter is 8 mm (HRB400), and the spacing is 100 mm. At the same time, the BFRP bars were polished smoothly with a grinder in the span position of the beam, and wiped repeatedly with alcohol as well as paper towels several times. Strain gauges were attached to the span position of the beam in order to measure the strain in the span of the beam, and the strain gauges were BX120-3AA. The fabrication of the reinforcement cage is shown in Figure 3.

(2) Casting of specimens. In the casting stage of the specimens, the casting method of the concrete beams with a full section added with steel fibers and the concrete beams with partial section added with steel fibers were different in this production according to the test requirements. First of all, for concrete beams with steel fibers added to the full section, the materials such as cement, gravel, and steel fibers need to be weighed strictly according to the ratio, and the weighed cement, as well as the aggregates, are put into the mixer for 5–6 minutes of dry mixing, and then water, as well as other materials such as steel fibers, are added for mixing. Then the mixed mixture is put into the prefabricated grinder and pounded with a pounding bar. As the steel fiber is added, the fluidity is poor, so the pounding time should be extended and the mixing should be stopped only after the steel fiber is evenly distributed. For the test beams with steel fibers added only in the compression zone, the weighing method is the same as that of the full-section concrete beams with steel fibers added. The difference is that when pouring, the part with steel fibers needs to be poured first, and then the plain concrete part is poured. This is because the density of steel fibers is high, in order to prevent the steel fibers from sinking during vibration, which will affect the test.

(3) Post-maintenance. After the completion of pouring, maintenance at least 24 h, then demolding, while covering a layer of wool felt, daily wet water maintenance, maintenance 28 days, production of finished products as shown in Figure 4.

2.4. Experiment with Loading and Testing Content. The test beam adopts the loading method of four-point bending and static load graded loading. The test beam was loaded with 10 kN per stage before cracking and 15 kN per stage after cracking, and the load gradient was reduced when the test beam was near cracking and failure. After each level of load is loaded, it needs to be held for 3 minutes, and the data is collected after the data is stable.

The main data collected are: (1) mid-span deflection; (2) top concrete strain; (3) initial crack load and ultimate load. In this experiment, displacement gauges were set at 1/3 of the beam mid-span and at the beam end, and a displacement gauge was also set at the upper end of the beam support to test the displacement of the beam support. The setup of

<table>
<thead>
<tr>
<th>Table 1: Physical and mechanical properties of BFRP bars.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity (GPa)</td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>BFRP bars</td>
</tr>
</tbody>
</table>

Figure 1: Stress-strain curves of BFRP bars.
resistance strain gauges, displacement gauges, and load cells is shown in Figure 5.

### 3. Analysis of Test Results

#### 3.1. Test Phenomenon and Failure Process.

During the four-point bending test of the beam, six BFRP failure modes of the reinforced test beams are the same, all of which are the super-reinforced failure of the crushed concrete in the compression zone, as shown in Figure 6.

When the load was loaded to 0.16Pu~0.19Pu, a small number of vertical micro-cracks appeared in the pure bending section of the test beam. With the increase of the load, the height of the micro-cracks extended upward, and Figure 2: Specimen size. (a) Side view of test beam. (b) B1 section. (c) B2/3/4 section. (d) B5 section. (e) B6 section. (f) B7 section. 

Table 2: Mix proportions of specimens.

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>$V_f$ (%)</th>
<th>Water (kg)</th>
<th>Cement (kg)</th>
<th>Fly ash (kg)</th>
<th>Sand (kg)</th>
<th>Stone (kg)</th>
<th>Fiber reinforced concrete layer height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0.00%</td>
<td>187</td>
<td>420</td>
<td>23</td>
<td>549</td>
<td>1280</td>
<td>0</td>
</tr>
<tr>
<td>B2</td>
<td>0.50%</td>
<td>187</td>
<td>420</td>
<td>23</td>
<td>746</td>
<td>1079</td>
<td>180</td>
</tr>
<tr>
<td>B3</td>
<td>1.00%</td>
<td>187</td>
<td>420</td>
<td>23</td>
<td>743</td>
<td>1069</td>
<td>180</td>
</tr>
<tr>
<td>B4</td>
<td>1.50%</td>
<td>187</td>
<td>420</td>
<td>23</td>
<td>735</td>
<td>1050</td>
<td>180</td>
</tr>
<tr>
<td>B5</td>
<td>1.00%</td>
<td>187</td>
<td>420</td>
<td>23</td>
<td>743</td>
<td>1069</td>
<td>210</td>
</tr>
<tr>
<td>B6</td>
<td>1.00%</td>
<td>187</td>
<td>420</td>
<td>23</td>
<td>742</td>
<td>1062</td>
<td>300</td>
</tr>
<tr>
<td>B7</td>
<td>1.00%/0.5%</td>
<td>187</td>
<td>420</td>
<td>23</td>
<td>742</td>
<td>1063</td>
<td>180</td>
</tr>
</tbody>
</table>
the cracks gradually became wider. When loaded to 0.5Pu, oblique cracks appeared in the shear span of the test beam, which rapidly extended from the bottom of the beam to the loading point. At this time, there were many micro-cracks in the pure bending section of the beam. Compared with the test beam B1, the partial BFRP reinforced concrete beam and the BFRP reinforced full-section steel fiber concrete beam are relatively stable in the process of crack propagation. When the load reaches 0.9Pu, the concrete at the lower part of the test beam gradually begins to fall off. Under the action of the load, the main inclined crack is also gradually expanding and the growth rate is much higher than that in the normal use state.

3.2. Analysis of Test Results. The results of this test are shown in Table 3.

For the test beam with a 0.5% steel fiber incorporation rate, the ultimate load is 179.02 kN for the steel fiber thickness of 180 mm in the compression zone (B2), which is 8.67% higher than that of the test beam without steel fiber (B1). For the test beams (B3, B5, and B6) with a 1% steel fiber incorporation rate, the ultimate loads were increased
by 13.28%, 14.61%, and 17.64%, respectively, compared to the beam (B1). For 1%/0.5% steel fiber admixture rate (B7), the ultimate load is 195.41 kN, which is 18.62% elevated compared to the beam (B1). For a 1.5% steel fiber admixture rate, the ultimate load is 219.78 kN for a thickness of 180 mm in the compression zone (B4), which is 33.41% higher than that of the beam (B1). For beams with a steel fiber concrete layer height of 180 mm (B2, B3, B4), the ultimate load was increased by 1.18% and 2.64%, respectively, with the increase of steel fiber content compared to the former.

The determination of the deflection in the span of the beam shows that the deflection variation tends to increase with the load change before reaching the initial cracking load. However, after reaching the initial cracking load, the overall stiffness of the test beams decreased and the deflection increased significantly with the application of the load. For BFRP reinforced steel fiber concrete beams (B2–B7) the mid-span deflection is about 4%~21% smaller than that of beam (B1). For beams with a steel fiber concrete layer height of 180 mm (B2, B3, B4), the ultimate load was increased by 1.18% and 2.64%, respectively, with the increase of steel fiber content compared to the former.

4. Calculation and Research on Deflection of BFRP Reinforced Partial Steel Fiber Concrete Test Beam

4.1. Beam Deflection Calculation Method Based on Effective Moment of Inertia Method. Compared with ordinary steel bars, BFRP bars have a smaller elastic modulus, and initial cracks are prone to appear at the bottom of the beam. The cracks at the bottom of the beam will make the concrete in the tension zone no longer a complete section, and the bending stiffness of the bottom will be smaller than that of the upper part of the beam, which will eventually make the beam The internal stiffness is no longer uniform. At this time, if the deflection calculation method recommended by the Chinese code is still used, the results obtained are quite different from the test values. Therefore, it is necessary to find a new deflection calculation method to calculate the deflection of BFRP reinforced concrete beams. Different countries have different methods for calculating the deflection of test beams, especially for test beams using BFRP bars, there are many recommended methods, and a more commonly used deflection calculation method is the effective moment of inertia method recommended by the American ACI Code [25] to calculate the deflection of the BFRP reinforced beam.

According to the recommendation of the ACI code [25], the moment of inertia of the BFRP reinforced concrete test beam before cracking is denoted by $I_g$, and the equivalent moment of inertia of the section is used after the initial crack is generated.

According to the recommendation of the ACI code [25], when the actual bending moment $M$ is greater than the cracking moment $M_{cr}$, the calculation method of the inertia moment of the test beam is as follows:

$$I_{eq} = \frac{I_g}{n_f}$$

\[n_f = \frac{E_f}{E_c}\]

Table 3: Test results.

<table>
<thead>
<tr>
<th></th>
<th>Cracking load $P_c$/KN</th>
<th>Ultimate load $P_u$/KN</th>
<th>Ultimate compressive strain $\varepsilon$</th>
<th>Maximum deflection at mid-span $\omega$/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>29.00</td>
<td>164.74</td>
<td>1621.52</td>
<td>21</td>
</tr>
<tr>
<td>B2</td>
<td>33.71</td>
<td>179.02</td>
<td>2253.32</td>
<td>24</td>
</tr>
<tr>
<td>B3</td>
<td>34.43</td>
<td>186.61</td>
<td>2309.81</td>
<td>23</td>
</tr>
<tr>
<td>B4</td>
<td>35.19</td>
<td>219.78</td>
<td>3613.92</td>
<td>26</td>
</tr>
<tr>
<td>B5</td>
<td>34.90</td>
<td>188.81</td>
<td>2922.72</td>
<td>24</td>
</tr>
<tr>
<td>B6</td>
<td>37.62</td>
<td>193.80</td>
<td>3289.51</td>
<td>26</td>
</tr>
<tr>
<td>B7</td>
<td>36.84</td>
<td>195.41</td>
<td>2590.23</td>
<td>25</td>
</tr>
</tbody>
</table>
I_e = \frac{I_{cr}}{1 - \frac{M_{cr}}{M_a}} \leq I_g. \quad (1)

In the formula, \( I_e \) is the effective moment of inertia of the beam after the crack appears, \( I_g \) is the initial effective moment of inertia of the beam, and the calculation formula is:

\[
I_g = \frac{1}{3} b \left[ x_0^3 + (h_0 - x_0)^3 \right] + (n_f - 1) A_f (h_0 - x_0)^2. \quad (2)
\]

\( M_a \) is the span section bending moment, \( M_{cr} \) is the cracking section bending moment, \( \gamma \) is the characteristic parameter, and the calculation formula is:

\[
\gamma = 1.72 - 0.72 \left( \frac{M_{cr}}{M_a} \right). \quad (3)
\]

Taking the neutral axis as the boundary and the principle of the equal area of the upper and lower compression and tension zones, the following equilibrium equation can be obtained:

\[
A_0 = bx_{cr} + n_f A_f. \quad (4)
\]

The static moment of the converted section to the compression zone is:

\[
S_1 = \frac{1}{2} bx_{cr}^2. \quad (5)
\]

The static moment of the converted section to the tension zone is:

\[
S_2 = n_f A_f (h_0 - x_{cr}). \quad (6)
\]

From the principle of the equal area of the upper and lower tension and compression areas, namely: \( S_1 = S_2 \), the formula can be obtained:

\[
\frac{1}{2} bx_{cr}^2 = n_f A_f (h_0 - x_{cr}). \quad (7)
\]

In the formula, \( x_{cr} \) is the height of the concrete compression zone of the cracked section.

From this it follows:

\[
x_{cr} = \frac{\sqrt{(n_f A_f)^2 + 2bn_f A_f h_0 - n_f A_f}}{b}. \quad (8)
\]

The moment of inertia of the cracked section:

\[
I_{cr} = \int_0^{x_{cr}} by^2 + n_f A_f (h_0 - x_{cr})^2
\]

\[
= \frac{1}{3} bx_{cr}^2 + n_f A_f (h_0 - x_{cr})^2. \quad (9)
\]

Before the cracks appear, the moment of inertia of the BFRP reinforced steel fiber reinforced concrete test beam before cracking: \( I_g \) can be calculated with reference to formula 2. After the cracks appear, due to the existence of steel fibers, the beam is subjected to complex stress, and the height of the compression zone is moved upward. The joint force of the steel fibers and the beam increases the bearing capacity and ultimate compressive strain, so that the deflection development of the beam is suppressed. The method of the original ACI code calculates the moment of inertia of the cracked section of the beam, and the calculated results are far from the test results. In view of this, this study refers to the original ACI standard method and refers to the "calculation formula for the deflection of the reinforced test beam with steel fibers in the tension zone" proposed by Professor Zhu Haitang's team [26], the formula for calculating the moment of inertia of cracking section of reinforced concrete beams with steel fibers in the full section and partial section in the compression zone is derived.

4.2. Calculation Method of Full-Section Steel Fiber Reinforced Concrete Test Beam \( I_{cr} \). According to the suggestion of literature [26], the steel fiber at the bottom of the test beam also plays the same tensile effect as the BFRP bar. In order to simplify the calculation, the steel fiber can be equivalently simplified into a "special bar".
Equivalent simplification should follow the following two principles: (1) the height of the simplified steel fiber as a whole remains unchanged. (2) The equivalent steel fiber form center is equal to the average value of the distance $d_m$ from the form center to the neutral axis of a single fiber. At the same time, it is assumed that under the service load, during the loading process of the BFRP reinforced steel fiber reinforced concrete beam, the steel fiber in the tension zone is still in the working state and has not been pulled out, and the equivalent converted section after cracking is shown in Figure 9.

According to the principle of equal area moments of the neutral axis, the following equation can be obtained:

$$I_{cr} = \frac{1}{3} bx_{cr}^3 + n_f A_f (h_0 - x_{cr})^2 + n_f \alpha_{sf} \left( \frac{h - x_{cr}}{2} \right)^2$$

(12)

$$b_{sf} = \frac{n_f \alpha_{sf}}{h - x_{cr}} = n_f \alpha_{sf} b v_f.$$  (13)

Simultaneous formulae (12) and (13) can be obtained:

$$I_{cr} = \frac{1}{3} bx_{cr}^3 + n_f A_f (h_0 - x_{cr})^2 + \frac{1}{3} n_f \alpha_{sf} b v_f (h - x_{cr})^3.$$  (14)

For beams with different dosing of steel fibers in the upper and lower sections, as the deflection control of steel fiber concrete beams mainly depends on the steel fibers in the compression zone, for the tension zone section once cracked, the steel fibers in the tension zone are then launched to work, the main role of doping steel fibers in the tension zone is to delay the cracking cross-section oversize generation and improve the cracking load of the beam. In order to simplify the calculation, we can refer to the calculation method of this full section, and the steel fibers in...
the compression zone are fully distributed in the full section.

4.3. Calculation Method of Partial Steel Fiber Reinforced Concrete Test Beam \( I_{cr} \) in Compression Zone. Adding steel fibers in the compression zone of the section, but not adding steel fibers in the tension zone, can increase the ultimate load and ultimate compressive strain of the beam, thereby delaying the increase of the beam’s mid-span deflection. The crack section and the converted section are shown in Figure 10.

According to the equalization and axial area moments of the steel fiber reinforced concrete in the tension zone and the compression zone, it can be obtained:

\[
\frac{1}{2}b_{cr}x_{cr}^2 = n_fA_f(h_0 - x_{cr}) + n_s\eta_s\alpha_s n_m
\]

\[
d_m = \frac{h_{sf} - x_{cr}}{2},
\]

\[
n\alpha_{sf} = \eta_{sf}b(h_{sf} - x_{cr})v_f.
\]

It can be solved by formula (17):

\[
x_{cr} = \frac{\sqrt{\left(n_fA_f + n_s\eta_s\alpha_s h_{sf}b\right)^2 + 2b\left(1 - n_s\eta_s\alpha_s h_{sf}^2v_f^2\right)\left(n_fA_f h_0 + 1/2n_s\eta_s\alpha_s h_{sf}^2b\right) - \left(n_fA_f + n_s\eta_s\alpha_s h_{sf}b\right)^2}}{b\left(1 - n_s\eta_s\alpha_s h_{sf}^2v_f^2\right)}
\]

(16)

Since the results of this calculation \( x_{cr} \) are all smaller than \( h_{sf} \), the moment of inertia \( I_{cr} \) of the cracked section can be obtained from Figure 10 and the formula of the parallel shift axis:

\[
I_{cr} = \frac{1}{3}b_{cr}x_{cr}^3 + n_fA_f(h_0 - x_{cr})^2 + \frac{1}{3}n_s\eta_s\alpha_s h_{sf}^2b(h_{sf} - x_{cr})^2.
\]

(17)

4.4. Verification of Test Results. According to the above analysis, the calculation formula of the mid-span deflection of a simply supported beam under symmetrical concentrated load is as follows:

\[
\Delta = \frac{PS}{48E_I} \left(3L^2 - 4S^2\right),
\]

(18)

where \( P \) is the acting load, \( L \) is the calculated length of the beam, \( S \) is the distance from the sub-load to the support point, and \( E_I \) is the elastic modulus of the concrete.

According to the equalization and axial area moments of the steel fiber reinforced concrete in the tension zone and the compression zone, it can be obtained:

\[
\frac{1}{2}b_{cr}x_{cr}^2 = n_fA_f(h_0 - x_{cr}) + n_s\alpha_s\eta_s n_m,
\]

\[
d_m = \frac{h_{sf} - x_{cr}}{2},
\]

\[
n\alpha_{sf} = \eta_{sf}b(h_{sf} - x_{cr})v_f.
\]

It can be solved by formula (17):

\[
x_{cr} = \frac{\sqrt{\left(n_fA_f + n_s\eta_s\alpha_s h_{sf}b\right)^2 + 2b\left(1 - n_s\eta_s\alpha_s h_{sf}^2v_f^2\right)\left(n_fA_f h_0 + 1/2n_s\eta_s\alpha_s h_{sf}^2b\right) - \left(n_fA_f + n_s\eta_s\alpha_s h_{sf}b\right)^2}}{b\left(1 - n_s\eta_s\alpha_s h_{sf}^2v_f^2\right)}
\]

(16)

Since BFRP reinforced concrete beams have larger deformation than reinforced concrete beams, the design of BFRP reinforced concrete beams is usually controlled by the normal service limit. In this study, 0.4\( M_U \), 0.5\( M_U \), and 0.6\( M_U \) are taken as the deflections under normal use conditions. Where \( M_U \) is the bending moment under ultimate load. The corresponding load level and the deformation at the upward load level are calculated according to the modified deflection calculation formula. The comparison results between the calculated value and the test value are shown in Table 4.

It can be seen from Table 3 that the deflection of the beam calculated by the correction formula in this study is close to the test value. The average ratio of the test beam \( \Delta_{AVG}(\Delta_{EXP}/\Delta_{MOD}) \) is 0.944, and the deflection of the test beam calculated directly by the formula in the ACI specification is quite different from the test results, and the
Table 4: Calculated and tested values.

<table>
<thead>
<tr>
<th>Serial number</th>
<th>$0.4M_U$</th>
<th>$0.5M_U$</th>
<th>$0.6M_U$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta_{Exp}$</td>
<td>$\Delta_{Mod}$</td>
<td>$\Delta_{ACI}$</td>
</tr>
<tr>
<td>B3</td>
<td>8.78</td>
<td>9.84</td>
<td>14.96</td>
</tr>
<tr>
<td>B4</td>
<td>5.49</td>
<td>7.96</td>
<td>16.05</td>
</tr>
<tr>
<td>B5</td>
<td>6.47</td>
<td>8.20</td>
<td>14.80</td>
</tr>
<tr>
<td>B6</td>
<td>6.04</td>
<td>5.99</td>
<td>12.88</td>
</tr>
<tr>
<td>B7</td>
<td>6.14</td>
<td>6.09</td>
<td>13.11</td>
</tr>
</tbody>
</table>

Note: $\Delta_{mod}$ is the calculated value obtained by the calculation method in this study, and $\Delta_{exp}$ is the experimental value.
obtained results are higher than the actual deflection of the test beam, and the calculation results are conservative. The reason may be that the recommended formula of the American ACI code does not consider the strengthening and toughening effect of steel fibers on BFRP-reinforced concrete beams. In order to more intuitively observe the degree of agreement between the correction formula and the test value, Figure 11 is a comparison diagram of beam deflection.

5. Conclusions

In this study, the influence of steel fiber content, reinforcement type, and layer thickness mixed with steel fiber on the deflection of the test beam is analyzed. According to the test results of this test, the deflection calculation formula of the BFRP reinforced steel fiber (full section/compression area reinforcement) concrete test beam is established. The main conclusions are as follows:

1. The integrity of partial steel fiber reinforced concrete beams with BFRP bars was good during the test, and there was no shear slip at the overlapping pouring interface of the steel fiber reinforced concrete and ordinary concrete during the bending process. The bending damage form is consistent with the damaged sign of the super-reinforced beam.

2. The incorporation of steel fibers improved the flexural performance of BFRP reinforced concrete beams to some extent, and the mid-span deflection of BFRP reinforced concrete beams decreased as the number of steel fibers incorporated and the height of the steel fiber concrete layer increased.

3. The influence of the thickness of the steel fiber concrete layer on the span deflection of the beam is not a major factor compared with the amount of steel fiber, so the actual project can appropriately reduce the amount of steel fiber in the concrete in the tensile zone to achieve the desired purpose of incorporating steel fiber in the full section while saving costs.

4. On the basis of the deflection formula recommended by the ACI code and the modified formula provided by Zhu Haitang’s team [92] of Zhengzhou University, the deflection calculation formulae for full-section steel fiber concrete beams with BFRP reinforcement and partial-section steel fiber concrete test beams in the compression zone suitable for this test were derived based on the test results, and the formula calculation results were in good agreement with the actual values.

5. For concrete beams with different amounts of steel fibers in the upper and lower sections, the method suggested in this study can be referred to, and the calculated results are more in line with the test results.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.
References


