Finite Element Analysis on Cracking Resistances of Recycled Aggregate Concrete Beams with Hybrid Fibers

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Abstract. In order to improve the mechanical properties and cracking resistances of recycled aggregate concrete, the influences of the volume incorporation rates of polypropylene fibers and steel fibers on the hybrid fiber recycled aggregate concrete beams are analyzed by finite element. The results show that: Compared with the ordinary RAC beams, the cracking load, the mid span deflection and the maximum compressive stress of HFRAC beams are larger under the initial cracking state. The yield load and maximum compressive stress of HFRAC beams vary little, and the mid span deflection increases or decreases under the yield state. HFRAC beams have greater stiffness and better ductility. Through theoretical calculation and finite element analysis, the formula for calculating the cracking moment of HFRAC beams is derived.

1. Introduction
Because of the large porosity, small density and internal micro cracks in the recycled aggregate, the mechanical properties and cracking resistances of recycled aggregate concrete (RAC) are poor compared with the ordinary concrete [1-4]. In recent years, domestic and foreign researches show that adding polypropylene fibers into RAC can improve the cracking resistance, impermeability and impact resistance [5-8]. Adding steel fibers to RAC can improve cube compressive strength, splitting tensile strength and flexural strength to a certain extent [9-12]. For example, the research results of Hecheng Qin [5] show that with the increase of polypropylene fiber content, the early cracking resistances of RAC are significantly enhanced. The test results of Aijiu Chen [11] show that the compressive strength of RAC increases with the increase of steel fiber content. The test results of Fen Yang [12] show that when the steel fiber content is 1%, the splitting tensile strength of RAC increases by 15%-21%, and the flexural strength increases by 17%-40%. Therefore, in view of the poor mechanical properties and cracking resistances of RAC, polypropylene fibers and steel fibers are mixed into RAC at the same time. The effect of different volume incorporation rates of hybrid fiber on the cracking load, yield load and mid span deflection of RAC beams are analyzed by finite element method, which provides a theoretical basis for practical engineering application of RAC.

2. Research scheme and modeling process

2.1. Research scheme
In this paper, 10 groups of RAC beams were designed. By changing the volume incorporation rates of polypropylene fibers and steel fibers, the cracking load, yield load and mid span deflection of hybrid fiber recycled aggregate concrete (HFRAC) beams were studied. The length of the beams is 1500mm, the span is 1200mm, and the section size is 150mm×250mm. The longitudinal tensile steel bar adopts
2.14 (HRB400 grade steel), the reinforcement ratio is 0.96%, the frame reinforcement adopts 2 8 (HRB335 grade steel), and the stirrup adopts Φ8@100 (HPB300 grade steel, double limb hoop). In order to exclude the effect of shear stress on the mechanical properties of normal section of specimens, the pure bending section with 400mm length is left in the middle span. The design scheme is shown in table 1, and the structural diagram of RAC beams is shown in figure 1.

Table 1. Design of test scheme

| Test NO. | Specimen number | Polypropylene fiber(%) | Steel fiber (%) | Axial compression strength(MPa) | Splitting tensile strength(MPa) | Modulus of elasticity (MPa) |
|----------|-----------------|------------------------|-----------------|-------------------------------|-------------------------------|-----------------------------|
| 1        | RC              | 0                      | 0               | 27.0                          | 2.15                          | 21400                       |
| 2        | P1S1            | 0.075                  | 0.5             | 24.1                          | 2.59                          | 20900                       |
| 3        | P1S2            | 0.075                  | 1.0             | 23.9                          | 2.91                          | 21500                       |
| 4        | P1S3            | 0.075                  | 1.5             | 23.5                          | 3.31                          | 22900                       |
| 5        | P2S1            | 0.1                    | 0.5             | 24.9                          | 2.78                          | 21000                       |
| 6        | P2S2            | 0.1                    | 1.0             | 24.6                          | 3.01                          | 21600                       |
| 7        | P2S3            | 0.1                    | 1.5             | 24.1                          | 3.31                          | 22000                       |
| 8        | P3S1            | 0.125                  | 0.5             | 26.2                          | 2.31                          | 20800                       |
| 9        | P3S2            | 0.125                  | 1.0             | 26.2                          | 2.79                          | 23100                       |
| 10       | P3S3            | 0.125                  | 1.5             | 26.5                          | 3.09                          | 23300                       |

Note: 1) RC is a recycled aggregate concrete specimen; 2) P1, P2, P3: The volume incorporation rates of polypropylene fibers are 0.075%, 0.1%, 0.125% respectively; 3) S1, S2, S3: The volume incorporation rates of polypropylene fibers are 0.5%, 1.0%, 1.5% respectively.

2.2. Modeling process

In order to better simulate the cracking resistances of RAC beams, the separated model is used to simulate the finite element [13], that is, the reinforcement and concrete are regarded as two different units respectively. RAC is analyzed by SOLID65 element, and the longitudinal tensile steel bar, the frame reinforcement and the stirrup are selected by LINK8 unit. In order to prevent the stress concentration, four rigid plates with 50mm×150mm are simulated at the top and the bottom of the beams. The finite element model of RAC beams is shown in figure 2, and the finite element model of reinforcements is shown in figure 3. The Poisson’s ratio of RAC is 0.20, and the Poisson’s ratio of reinforcement is 0.30. The finite element analysis of the reinforcement in the beam use bilinear kinematic model (BKin) and Von Mises yield criterion. In the process of solving, the shear transfer coefficients of concrete opening crack and closed crack are 0.5 and 0.95 respectively, and the uniaxial compressive strength is -1, that is, the crushing function is closed. The number of loading step iterations is set to 60, the output frequency is set to write every substep, the maximum cycle number is set to 20 in the Nolinear option. The displacement convergence criterion is used to analyze, and the convergence accuracy is set to 1.5%.
3. Results and analysis

3.1. Analysis of loads
Figure 4 shows the initial cracking loads of RAC beams. According to the figure, the cracking load of group RC is 10.58kN, and the cracking loads of RAC beams are obviously increased with the addition of hybrid fibers. Among them, the maximum cracking load of group P3S3 is 21.63kN, which is 104.4% higher than that of group RC. This is because the fibers are disorderly in RAC. When the concrete is subjected to the force, the disorderly fibers strengthen the constraint effect of the concrete matrix, and improve the tensile strength of RAC, thus the cracking loads of RAC beams are improved. Figure 5 shows the yield loads of RAC beams. According to the figure, the yield load of group RC is 86.67kN, and the yield loads of RAC beams vary little with the addition of hybrid fibers. Among them, the maximum yield load of group P3S3 is 87.13kN, which is higher than that of group RC by 0.46kN.

3.2. Analysis of mid span deflections
Figure 6 shows the mid span deflections of RAC beams under the initial cracking state. According to the figure, the mid span deflection of group RC is 0.10mm, and the mid span deflections of RAC beams increase with the addition of hybrid fibers. Among them, the maximum mid span deflection of
group P2S2 is 0.19mm, which is 102.1% higher than that of group RC. Figure 7 shows the mid span deflections of RAC beams under the yield state. According to the figure, the mid span deflection of group RC is 2.46mm, and the mid span deflection of RAC beams increase or decrease with the addition of hybrid fibers. Among them, the maximum mid span deflection of group P3S1 is 2.70mm, which is 10.1% higher than that of group RC, and the minimum mid span deflection of group P2S3 is 2.23mm, which is 9.2% lower than that of group RC.

3.3. Analysis of maximum compressive stresses
Figure 8 shows the maximum compressive stresses of RAC beams under the initial cracking state. According to the figure, the maximum compressive stress of group RC is 22.40MPa, and the maximum compressive stresses of RAC beams increase with the addition of hybrid fibers. Among them, the maximum compressive stress of group P3S3 is 3.24MPa, which is 105.3% higher than that of group RC. Figure 9 shows the maximum compressive stresses of RAC beams under the yield state. According to the figure, the maximum compressive stress of group RC is 22.40MPa, and the maximum compressive stresses of RAC beams vary little with the addition of hybrid fibers. Among them, the maximum compressive stress of group P3S2 is 24.45MPa, which is 9.1% higher than that of group RC.

3.4. Analysis of load-deflection curves
Figure 10 shows the load-deflection curves of RAC beams. According to the figure, the deflections increase linearly with the increase of load when the load is small. When the beams are cracking, the curves change, the stiffness decreases obviously, and the deflections increase rapidly. Compared with RC beam, the cracking loads of HFRAC beams increase significantly. Under the same loads, the deflections of HFRAC beams are smaller, that is, the stiffness of HFRAC beams is larger, and the ductility of HFRAC beams is better.

4. Calculation of cracking moment of HFRAC beams
Referring to the design code for hydraulic concrete structures (SL 191-2008), the formulas for calculating cracking moment [14] of reinforced concrete beams are as follows:
\[ M_{cr} = \gamma_m f_{th} I_0 \left( h - y_0 \right) \]  
\[ I_0 = \left( 0.083 + 0.19\alpha_e \rho \right) bh^3 \]  
\[ y_0 = \left( 0.5 + 0.425\alpha_e \rho \right) h \]

Where: \( M_{cr} \) —cracking moment of reinforced concrete beams; \( \gamma_m \)—the basic value of the influence coefficient of the section resistance to moment plasticity, take \( \gamma_m = 1.55 \) for rectangular cross section; \( f_{th} \)—standard value of concrete axial tensile strength; \( I_0 \)—conversion section inertia moment; \( y_0 \)—section centroid axis to drawing edge distance; \( \alpha_e \)—ratio of elastic modulus of steel bar to elastic modulus of concrete; \( \rho \)—reinforcement ratio of longitudinal tensile steel bar; \( b \)—breadth of section; \( h \)—depth of section.

Considering the poor cracking resistance of RAC, the formula (1) is modified. The formula for calculating the cracking moment of RAC beams is as follows:

\[ M_{cr}^R = KM_{cr} \]  

Where: \( M_{cr}^R \)—cracking moment of RAC beams; \( K \)—correction coefficient of cracking moment of RAC beams.

According to the results of finite element analysis and calculation, \( K = 2.116 / 9.233 = 0.229 \). Considering that the hybrid fibers have obvious effect on the cracking moment of RAC beams, the formula (4) is corrected and the calculation formula of the cracking moment of HFRAC beams is obtained by fitting the test data.

\[ M_{cr,f}^R = M_{cr}^R \left( 1 + \beta_f \lambda_f + \beta_p \lambda_p \right) = 0.229 M_{cr} \left( 1 - 0.321 \lambda_f + 1.295 \lambda_p \right) \]

Where: \( M_{cr,f}^R \)—cracking moment of HFRAC beams; \( \beta_f, \beta_p \)—the influence factors of cracking moment of steel fiber and polypropylene fiber, respectively; \( \lambda_f \)—characteristic parameters of steel fiber content, \( \lambda_f = \rho_f l_f / d_f, \rho_f \)—volume incorporation rate of steel fiber, \( l_f \)—length of steel fiber, \( d_f \)—diameter of steel fiber, the ratio of length to diameter of steel fiber in this test is 50; \( \lambda_p \)—characteristic parameters of polypropylene fiber content, \( \lambda_p = \rho_p l_p / d_p, \rho_p \)—volume incorporation rate of steel fiber, \( l_p \)—length of steel fiber, \( d_p \)—diameter of steel fiber, the ratio of length to diameter of steel fiber in this test is 350.

| Test NO. | Specimen number | \( M_{cr,f}^{RC} \) (kN·m) | \( M_{cr,f}^{RT} \) (kN·m) | \( M_{cr,f}^{RC} / M_{cr,f}^{RT} \) |
|----------|-----------------|-----------------|-----------------|-----------------|
| 1        | RC              | 2.114           | 2.116           | 0.999           |
| 2        | P1S1            | 3.221           | 3.370           | 0.956           |
| 3        | P1S2            | 3.377           | 3.360           | 1.005           |
| 4        | P1S3            | 3.529           | 3.360           | 1.050           |
| 5        | P2S1            | 3.768           | 3.382           | 1.114           |
| 6        | P2S2            | 3.815           | 4.312           | 0.885           |
| 7        | P2S3            | 3.919           | 3.377           | 1.160           |
| 8        | P3S1            | 3.395           | 3.374           | 1.006           |
| 9        | P3S2            | 3.787           | 3.373           | 1.123           |
| 10       | P3S3            | 3.948           | 4.327           | 0.913           |

Table 2 shows the comparison between the calculated values \( M_{cr,f}^{RC} \) and the simulated values \( M_{cr,f}^{RT} \) of cracking moment of HFRAC beams. According to the table, the average value of \( M_{cr,f}^{RC} / M_{cr,f}^{RT} \) is 1.021, the standard deviation is 0.087, and the coefficient of variation is 0.085. It shows that the calculated values are in good agreement with the simulated values. The formula can be applied to the calculation of cracking moment of HFRAC beams.
5. Conclusions
In this paper, the volume mixing ratios of polypropylene fibers and steel fibers are changed, and the cracking resistances of RAC beams are analyzed. The following conclusions are obtained:

(1) In the initial cracking state, the cracking loads of HFRAC beams increase significantly, while the mid span deflections and maximum compressive stresses increase.

(2) In the yield state, the yield loads and maximum compressive stresses of HFRAC beams vary little, while the mid span deflections increase or decrease.

(3) Compared with ordinary RAC beams, HFRAC beams have greater stiffness and better ductility.

(4) In view of the obvious improvement of the cracking moment of HFRAC beams, the formula of the cracking moment of HFRAC beams is put forward: \( M_{cr,f} = 0.229 M_{cr}(1 - 0.321 \lambda_f + 1.295 \lambda_p) \).

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