Experimental Study on Mechanical Properties of New Recycled Concrete Composite Beams

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Abstract. We made one of the new composite beam-column joint as tested specimen, and four specimens. By doing the model test under static load, we got some experimental results about specimens. For example, the cracking load, the ultimate bearing capacity, the load-deformation curves and the mechanical characteristic of the composite area of beam-column joint. We get conclusions as follow. The values of cracking load and ultimate bearing capacity of the new composite mixed using concrete and recycled concrete can be calculated by the formulas in Code for design of concrete structures (GB 50010-2010). As the structural style of the whole Cast-in-situ concrete specimen and the new composite mixed using concrete and recycled concrete is different, the law of the development of the deflection is similar, and we put forward modifier formula for calculating the bending rigidity. Adopting the structural with step-shaped composite area at the end of beam is useful for prevent cracks from running on, and the method can enhance its bearing capacity.

1. Introduction
Concrete composite structure is composed of a layer of concrete poured on prefabricated parts, which belongs to assembled integral structure. Compared with cast-in-situ structure, composite structure can save materials, make construction convenient and shorten construction period. Compared with assembled structure, composite structure has better integrity, stronger stiffness and excellent seismic performance[1]. In addition, the construction waste caused by the demolition of a large number of dilapidated buildings has brought serious environmental problems. In order to overcome the shortcomings of easy breakage in transportation and low strength in construction, this paper adds recycled concrete as core on the basis of U-shaped precast composite beams through experimental study, and makes the core of both ends of beams into step-shaped sections to increase the overlapping area of beam-column joints so as to improve the integrity of the structure and reduce self-weight. At the same time, all cast-in-place parts are recycled. Concrete, to maximize the use of renewable resources. Based on the review of references, no relevant research on the new recycled concrete composite beams proposed as this paper has been found[2-4]. In this paper, the mechanical properties of beam-column joints are selected as the research object. Through model tests, the mechanical properties such as the flexural bearing capacity, stiffness and crack propagation are studied to provide reference for structural design and engineering application.

2. Test Survey

2.1. Design and Fabrication of Specimens
A short compressive column is installed in the middle of the beam-type member. Taking CRCB as an example, the model consists of three parts: the left prefabricated part, the right prefabricated part and the cast-in-situ part (including the composite part of the beam and the middle short column). The specific design is as follows:

1) Prefabricated part design

The end of the beam consists of prefabricated U-shaped groove and core. The cross-section in the middle of the beam is rectangular, and its size is 200 mm*170 mm. The cross-section size of the core is 100 mm x 100 mm, as shown in Fig. 1(a). The width of U-shaped part is 200 mm, the thickness of bottom plate is 70 mm, the height of side wall is 100 mm, and the thickness is 50 mm, as shown in Figure 1(b). The overlap surface at the end of the beam is a stepped type, which is divided into three steps. The width and height of the first step are 70 mm, the width and height of the second step are 50 mm, the height of the third step is 50 mm, and the connection angle at the bottom of the step is 45 degrees, as shown in Figure 1(c), (d).

![Figure 1](image)

Figure 1. The design drawing for the prefabricated part for the CRCB

The design of the step-shaped type mainly considers the following advantages: firstly, it can increase the contact area between the old and new concrete, secondly, it can prevent the development of cracks by changing the crack development path, so as to improve the bearing capacity of the structure. The prefabricated parts of different specimens are made differently, as shown in Table 1.

| Specimen Type | U-shaped material | Core material | Types of overlapping surfaces at the end of beams |
|---------------|-------------------|---------------|--------------------------------------------------|
| CRCB          | ordinaryC30       | recycledC30   | Step-shape                                       |
| CRCB-1        | ordinaryC30       | recycledC30   | 45degree incline                                 |
| CCCB          | ordinaryC30       | ordinaryC30   | Step-shape                                       |
| RRCB          | recycledC30       | recycledC30   | Step-shape                                       |

Reinforcement of beam bottom in prefabricated zone: longitudinal reinforcements are 2 grade 3 steel bars with 14mm diameter, and stirrups are 8mm@100 in diameter (in encrypted zone). The stirrups are embedded in prefabricated zone and the thickness of protective layer is 25mm. The strength grades of ordinary concrete and recycled concrete are both C30.

2) Overall design

Five beam-type specimens with cast-in-situ short columns were fabricated. Four of them were new recycled concrete composite beams (short cast-in-situ, precast and cast-in-situ). They were identified
as CRCB, CRCB-1, CCCB and RRCB respectively. Their longitudinal sections were shown in Figure 2. (a) - (d) and the other one was full-cast specimen ZJL, whose longitudinal section was shown in Figure 2. (e). The section of short column is $b \times H = 200 \text{ mm} \times 200 \text{ mm}$, the net height is 150 mm, and the section of rectangular beam on both sides of column is $b \times H = 200 \text{ mm} \times 270 \text{ mm}$. Before concreting the upper part of the overlap surface of the beam, the upper reinforcement bars of the beam should be installed. Recycled concrete is used in the upper part of the overlap surface of beams, ZJL and short columns, which are cast in situ.

Figure 2. (a) The longitudinal cross section drawing for CRCB

Figure 2. (b) The longitudinal cross section drawing for CRCB-1

Figure 2. (c) The longitudinal cross section drawing for CCCB

Figure 2. (d) The longitudinal cross section drawing for RRCB

Figure 2. (e) The longitudinal cross section drawing for ZJL

The reinforcement of each specimen is the same. The longitudinal reinforcement bars of the upper and lower part of the beam are two 14mm three-grade rebars, the stirrups are 8@100 in diameter, the
column reinforcement is four 20mm three-grade steel bars, and the stirrups are 8@50 in diameter, as shown in Figure 3.

![Figure 3](image)

Figure 3. The location of the rebar in all of specimens

The reinforcement ratio of longitudinal bars of beams is $\rho_s = 0.66\%$, and the total area of stirrups is 0.5% of the overlapping surface area, which is larger than 0.15% required in reference [3]. It can ensure that no shear failure occurs on the overlapping surface during the loading process, so all the specimens are beams with suitable reinforcement. The support is set to retract 150 mm at each end of the beam, the shear span length is $a = 500$ mm, the effective height is $h_0 = 235$ mm, so the shear span ratio is 2.13.

3) Test materials

The strength grades of ordinary concrete and recycled concrete are both C30, the water cement ratio is 0.42, and the replacement rate of recycled aggregate is 50%. The measured results show that the compressive strength of ordinary C30 concrete is 48.02N/mm$^2$, the axial compressive strength is 31.15N/mm$^2$, the axial tensile strength is 2.63N/mm$^2$, and the elastic modulus is 3.42e4 N/mm$^2$; the compressive strength of recycled C30 concrete is 42.99N/mm$^2$, the axial compressive strength is 27.39N/mm$^2$, the core tensile strength is 2.13 N/mm$^2$ and the elastic modulus is 1.91e4 N/mm$^2$.

2.2. Test Loading Scheme and Data Recording

In order to simulate the force at the end of the beam-column joint, the centralized loading mode is selected.

3. Test Results and Analysis

3.1. Comparative Analysis of Bearing Capacity

1) Calculation Formula

a) Calculation of Cracking Load

All the specimens of the new recycled concrete composite beams in this paper are designed as first-order composite beams. According to the Code for Design of Concrete Structures (GB50010-2010), they can be calculated as monolithic beams. Therefore, formulas 7.2.3 and 7.2.4 in the code are selected. The concrete formulas are as follows$^5$:

$$ M_{cr} = \gamma f_{tk} W_0 $$

$$ \gamma = \gamma_m (0.7 + \frac{120}{h}) $$

In the formula, $M_{cr}$—Cracking Load, $\gamma$—Plasticity Influence Coefficient of Resistance Moment of Concrete Section, $f_{tk}$—Standard Value of Concrete Tensile Strength, $\gamma_m$—Plasticity Influence Coefficient of Resistance Moment of Concrete Section, 1.55 according to table 7.2.4, h-section height, h<400, h=400, $W_0$—Converted of Elastic Resistance Moment at the Tension Edge of Section.

As the specimens are rectangular sections with single reinforcement, the following formulas$^6$ are obtained according to the formulas 7.1.1 and 7.1.2 in the Code for Design of Hydraulic Concrete Structures (SL191-2008):

$$ W_0 = \frac{0.0833 + 0.19a_E\rho}{0.5 - 0.425a_E\rho} \times b \times h^2 $$
In the formula, \( \alpha_E \)--the Elastic Modulus Ratio of Steel Bar to Concrete; \( \rho \)--Reinforcement Ratio of Rectangular Section.

b) Calculation of Ultimate Load

All specimens are beam-column joints, so the maximum bending moment will appear at the junction of short columns and beams. According to the formula 6.2.10-1-4 in the Code for Design of Concrete Structures (GB50010-2010), the following formula for calculating the ultimate bending moment is obtained\(^{[5]}\):

\[
M_u = \alpha_1 f_c b x \left( h_0 - \frac{x}{2} \right) \tag{4}
\]

In the formula, \( h_0 = 235 \text{mm}, x = \frac{f_y A_s}{\alpha_1 f_c b}, A_s = 308 \text{mm}^2, b = 200 \text{mm} \)

The tensile strength of reinforcing bars is measured yield strength, and the compressive strength of concrete is taken as the axial compressive strength of recycled concrete. Because the reinforcement and section size of each specimen are the same, the parameters of concrete are basically the same, and the loading mode is the same. Therefore, taking ZJL as an example, the calculation results show that the cracking load \( M_{cr} \) is 9.39 kN/m and the ultimate load \( M_u \) is 33.39 kN/m.

2) Contrastive Analysis of Measured and Theoretical Values

The theoretical cracking load of each specimen is 9.39 kN/m, while the actual cracking load is 10 kN/m. It can be seen that the actual value is close to the theoretical value. Therefore, the cracking load of new recycled concrete composite beams can be approximately calculated by formula (1) ~ (3).

The comparative analysis of the ultimate bearing capacity of the test and the theoretical calculation value is shown in Table 2. The ultimate bearing capacity of CRCB and CCCB is the highest, which is 1.11 times of the theoretical value; next is CRCB-1, whose ultimate bearing capacity is 1.04 times of the theoretical value, slightly higher than ZJL and RRCB; RRCB has the lowest ultimate bearing capacity, which is only 0.97 times of the theoretical value. The calculated values are based on ZJL.

From the comparison results, the formulas and related data used in the calculation are reliable.

Table 2. Theoretical values and measured values of ultimate bearing capacity for all of specimens

| Specimen number | \( M_{\text{th}}/\text{kNm} \) | \( M_{\text{act}}/\text{kNm} \) | \( M_{\text{th}}/M_{\text{act}} \) |
|-----------------|----------------|----------------|----------------|
| CRCB            | 37.5           | 33.64          | 1.11           |
| CRCB-1          | 35             | 33.64          | 1.04           |
| CCCB            | 37.5           | 33.64          | 1.11           |
| RRCB            | 32.5           | 33.39          | 0.97           |
| ZJL             | 33.75          | 33.39          | 1.01           |

From the comparison between the experimental ultimate bearing capacity of RRCB and ZJL and the theoretical calculated value, it can be concluded that the ultimate bearing capacity of RRCB and ZJL is similar, with only 3.8% difference. This shows that the new type of recycled concrete composite beams proposed in this paper is that the overlap surface at the end of the beams is a step type, and the prefabricated beams are divided into two parts, i.e. the core and the U type, and the beam stirrups are used as the shear connectors of the overlap surface. The purpose of improving the integrity and bearing capacity of the composite beams can be achieved.

Only from the material analysis, the ultimate bearing capacity of CRCB and CRCB-1 should be very close, but the actual difference between them is as high as 7.1%. The only variable between them is that the end overlap surface of CRCB joint beam is ladder-shaped and the inclined surface of CRCB-1 specimen is 45 degrees. Therefore the structural bearing capacity can be improved by using stepped superimposed surface at the end of the beam compared with inclined superimposed surface.

3.2. Comparative analysis of specimen stiffness

1) Theoretical Calculation Stiffness

In calculating short-term stiffness, the formulas used in Li Changyong’s paper\(^{[7]}\) “Calculating method of flexural stiffness of reinforced concrete beams based on equivalent cross-section moment of inertia” are selected in this paper.
$B_s = \beta E_c I_0$  \hspace{1cm} (5)

$B_s$, the short-term flexural stiffness of the normal section of reinforced concrete beams. $\beta$, the reduction coefficient of the flexural stiffness of the normal section, when $M=M_{cr}$, the mean values of formulas (6) and (7) are measured. $E_c$, concrete elastic modulus, $I_0$, converted moment of inertia of the section.

Before cracking, $\beta$ is related to the accumulative damage of concrete in tensile zone, which can be expressed by the ratio of M to $M_{cr}$:

$$\beta = 0.85 \left(1 - 0.45 \frac{M}{M_{cr}}\right)$$  \hspace{1cm} (6)

The beta after cracking is related to the deformation of concrete in compression zone, the change and shape of concrete cracks in tension zone, the stress of tension steel bar in cracking zone and the uniformity of steel bar between cracks\cite{7}. Referring to the calculation model of section flexural stiffness of pre-stressed concrete beams and steel fiber reinforced all-lightweight concrete superimposed beams in normal service stage, $M / M_{cr}$ and $\alpha E \rho$, shown as:

$$\beta = \frac{0.85}{1 + \left(1.16 - M_{cr}/M\right) / (6\alpha E \rho)}$$  \hspace{1cm} (7)

The cracking load formula (1) is used to calculate the cracking load. The parameters of ZJL and CRCB are different for the whole cast-in-place beam specimens. The main difference lies in that all the ZJL sections are recycled concrete. The calculation is relatively simple. The ratio of stiffness of actual ZJL specimens to calculated stiffness $B'/B$ varies with the load as shown in Figure 4. The figure shows that the actual stiffness of the specimens is in good agreement with the calculated stiffness, and the ratio is basically maintained at about 1 with an average value of 1.006. It can be seen that the formula (1) - (3) are completely applicable to the whole cast-in-place beam specimens. The CRCB section is a composite section, and its $E_c I_0$ is larger than that of ZJL according to the composite section.

![Figure 4. The scatter diagram of load-for B' / B for CRCB and ZJL](image_url)

The ratio of calculated stiffness and that of actual CRCB specimens B'/B varies with load as shown in Figure 4. From the graph, it can be seen that before the cracking load reaches 40 kN, the actual specimen stiffness and the calculated stiffness are in good agreement, the ratio is 1.03 on average, but after cracking, the actual specimen stiffness and the calculated stiffness are not in good agreement, the ratio is 0.8 on average, and the discrete coefficient is CV=0.137. Therefore, if formula (7) is applied to the new recycled concrete composite beam, it needs to be revised. That is to say, the formula (8) is obtained by multiplying the correction coefficient by 0.8. The statistical results of the calculated values obtained by the new formula are shown in Fig. 10. At this time, the discrete coefficient is CV repair = 0.045, which is much less than the original 0.137. The discrete degree is obviously reduced, so the coincidence effect is better.

$$\beta = \frac{0.68}{1 + \left(1.16 - M_{cr}/M\right) / (6\alpha E \rho)}$$  \hspace{1cm} (8)

The load-B' / B of the CRCB specimen calculated by the modified formula is shown in Figure 5.
2) Contrastive analysis of actual stiffness

The actual stiffness of the specimens under various loads is calculated by the structural mechanics formula (9) and the measured mid-span deflection.

\[ a_f = \frac{F l^3}{48 EI} \]  

(9)

In the formula, \( a_f \) is the measured deflection value, \( F \) is the actual concentrated load, \( L \) is the calculation span of the specimen, \( l = 1200 \text{mm} \); \( EI \) is the stiffness of the specimen, and the load in the test process belongs to the short-term load. Therefore, short-term stiffness \( B_s \) is selected as the research object, i.e., the \( EI \) in formula (9) is replaced by \( B_s \). The load-stiffness curve of each specimen is shown in Figure 6.

Figure 6. The load- measured bending rigidity of all of specimens

Figure 7. The failure state for the NO.4 crack of CRCB-1

4. Conclusion

(1) The innovative structure of the new recycled concrete composite beam proposed in this paper is that the prefabricated beams are divided into two parts, i.e. core and U-shaped, and the overlapping surface at the end of the beam is a step-shaped shear connector with stirrups as the overlapping surface. The purpose of improving the integrity and bearing capacity of the composite beam is achieved. CRCB ultimate bearing capacity is 15.4% higher than RRCB, CRCB ultimate bearing capacity is 7.1% higher than CRCB-1. It shows that the use of step-shaped overlapping surface at the end of beam is more advantageous to the structural stress, it can further enhance the ultimate bearing capacity of specimens, and meets the requirements of green sustainable development.

(2) A modified formula of stiffness reduction factor beta of normal section after cracking of new recycled concrete composite beam-column joints is proposed. The discrete coefficient is decreased from CV=0.137 to CV repair=0.045, and the coincidence effect is good.

\[ \beta = 0.68 \frac{1}{1 + (1.16 - \frac{M_{cr}}{M}) \left(\frac{6\alpha E\rho}{6\alpha E\rho}\right)} \]

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