Analysis of the bearing capacity of the normal section of regional confined concrete flexural members

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Abstract. In this paper, a static failure test was carried out on a confined concrete beam and a normal reinforced concrete beam. The theoretical and experimental bearing capacity of ordinary reinforced concrete beams and regional confined concrete beams are analyzed. The experimental and theoretical calculation results show that the regional confined concrete beam can effectively increase the bearing capacity of the beam without changing the section size. Since ordinary reinforced concrete participates in the compression zone in order to consider the compression zone, the calculation formula for regional confined concrete beams given in the code is conservative.

1. Introduction

Traditional reinforced concrete beams are equipped with tension longitudinal bars in the tension zone to bear the tension generated by the bending moment, and the compression zone is jointly borne by concrete or concrete combined with the compression longitudinal bars. At the same time, stirrups are generally set in the beam, but the stirrups in the beam mainly play the role of erection and shear resistance, and the influence of its restraint on the structure is not considered. In the "Code for Design of Concrete Structures" [1], the ultimate strain of concrete for bending members is 0.0033. In fact, due to the restraint of stirrups in the beam, the ultimate strain and ultimate bearing capacity of concrete can be improved.

The "Code for Design of Concrete Structures" guarantees the proper reinforcement failure of reinforced concrete beams by limiting the height of the boundary compression zone of reinforced concrete beams. This means that as the beam bearing capacity requirements increase, the height of the beam section will increase, and the self-weight of the concrete structure will also increase significantly. At the same time, the floor height is greatly restricted, causing serious waste of resources. This is the main problem currently existing in traditional reinforced concrete beam structures.

The stirrups configured in traditional reinforced concrete beams are mainly used for shear resistance, without considering its restraint effect on concrete. Zhang Genyu [2] added section steel to the central area of the reinforced concrete beam, considered the effective restraint effect of section steel and stirrups when calculating its flexural bearing capacity, and converted this restraint effect into "extra" concrete compressive strength. However, the high confinement area of this confinement method is in the center area of the beam and the improvement of the elastic modulus of the concrete after confinement is not considered. Wang Suyan [3] wound CFRP in the mid-span plastic hinge zone of...
high-strength concrete beams and found that the ductility coefficient was increased by about 1.31-3.34 times, but the position of the maximum restraint strength of this form of restraint is still located in the core area. We know that in the working state of a simply supported beam, the area above the neutral layer is compressed and the area below the neutral layer is tensioned. In the case of proper reinforcement, the bearing capacity of the beam mainly depends on the compressive strength and ultimate strain of the concrete. Based on the method of imposing constraints where constraints are needed and the concept of effective constraints, Professor Xinming Cao\cite{4} of Guizhou University proposed the concept of regional constrained concrete. In the beam, we constrain the compression zone of the beam to increase the strength of its concrete, while the ultimate compressive strain of the concrete in the confinement zone increases.

2. Test plan

2.1. Specimen

In this experiment, one regional confined concrete beam and one ordinary concrete beam were designed. The beam span is 1.2m, the beam section is 150mm×300mm, and the stirrup spacing is 50mm. The reinforcement of each beam is shown in Figure 1. The concrete strength is C40. The measured concrete strength standard value is 40MPa, which is converted into the axial compressive strength value of 26.8MPa. The measured strength of the steel bars is shown in Table 1.

| Material | diameter(mm) | Yield Strength (MPa) |
|----------|--------------|----------------------|
| HRB400   | 25           | 442.5                |
| HRB400   | 22           | 464.5                |
| HRB400   | 10           | 529.5                |
| HRB400   | 8            | 491.0                |

Figure 1. Beam section reinforcement

In this experiment, one regional confined concrete beam and one ordinary concrete beam were designed. The beam span is 1.2m, the beam section is 150mm×300mm, and the stirrup spacing is 50mm. The reinforcement of each beam is shown in Figure 1. The concrete strength is C40. The measured concrete strength standard value is 40MPa, which is converted into the axial compressive strength value of 26.8MPa. The measured strength of the steel bars is shown in Table 1.
2.2. Loading device and test method
In this test, symmetrical loading was adopted at two points in the middle of the span. The structure failure test is carried out on the static table, and the process loading is carried out by controlling the load. In order to measure the displacement of components, displacement meters are arranged in the middle of the span, the loading point and the support respectively. The layout of the loading device and displacement gauge is shown in Figure 2. The distance from each loading point to the center of the support is 750 mm. Paste resistance strain gauges on the surface of steel and concrete to measure the transverse deformation of steel and concrete.

![Diagram of loading device and dial indicator arrangement](image)

Figure 2. Loading device and dial indicator arrangement

3. Theoretical analysis

3.1. Calculation of bearing capacity of ordinary super reinforced beam
When the super-reinforced member fails, the tensile longitudinal bar does not yield. Therefore, when calculating the bearing capacity of the super-reinforced member, the stress of the tension bar should be determined first. The strain and stress of the bar at any position of the section can be determined as:

\[
\varepsilon_{sl} = \frac{h_{0i} - x_{si}}{x_{si}}\varepsilon_{cu} = \varepsilon_{cu} \left( \frac{h_{0i} \beta_{1i}}{x_{si}} - 1 \right) = \varepsilon_{cu} \left( \frac{h_{0i} \beta_{1i}}{\varphi_{0i}} - 1 \right)
\]

(1)

\[
\sigma_{si} = E_{si} \varepsilon_{cu} \left( \frac{h_{0i} \beta_{1i}}{\varphi_{0i}} - 1 \right)
\]

(2)

For concrete with a strength class not greater than C50, formula (2) becomes:

\[
\sigma_{si} = 0.0033E_{i} \left( \frac{0.8h_{0i}}{\varphi_{0i}} - 1 \right)
\]

(3)

The above formula is a hyperbolic equation, which is brought into the balance equation, and the higher-order equation needs to be solved. According to the literature [5], \( \xi = \xi_{i} \) and \( \xi = 0.8 \frac{h_{0i}}{h_{0i}} \) can be used as boundary conditions to obtain the linear relationship between \( \sigma_{si} \) and \( \xi \):

\[
\sigma_{si} = f_{si} \left( \frac{h_{0i} \xi - 0.8h_{0i}}{h_{0i} \xi - 0.8h_{0i}} \right)
\]

(4)

The balance equation of super-reinforced components is:
\[ \alpha_f b f_c = \sum A_h \sigma_h \]  
\[ M = \sum A_c \sigma_c \left( h_0 - \xi h_0 / 2 \right) \]  

(5)  

(6)

Put the component size, test-measured steel bar strength, concrete compressive strength value and formula (4) into formula (5) to obtain \( \xi = 0.6 \). Bringing \( \xi \) into equations (4) and (6), the theoretical bearing capacity of ordinary reinforced concrete beams is calculated to be 364.7KN.

When calculating the bearing capacity of the bearing beam according to the limit reinforced beam, the bearing capacity calculation formula is:

\[ M = \alpha_f b f_{c0} \left( 1 - 0.5 \xi b \right) \]  

(7)

Incorporating the test data into equation (7), the bearing capacity of the limit reinforced beam is 353.7KN.

### 3.2. Calculation of bearing capacity of regional confined concrete beams

According to the "Technical Regulations for Regional Constrained Concrete Structures" [5], the compressive strength value of the restraint should meet the following requirements:

\[ f_{cc} = (1 + k) f_c \]  

(8)

Among them, the constraint coefficient is:

\[ k = (f_y \rho_s + f_y \rho_v) / f_c \]  

(9)

And \( k \geq 0.48 \)

\[ \frac{\rho_v}{\rho_s} \approx 1 \sim 1.5 \]  

(10)

If \( \rho_v \geq 1.5 \rho_s \), take \( \rho_v = 1.5 \rho_s \).

If \( \rho_v \leq \rho_s \), take \( \rho_v = \rho_s \).

\( \rho_v \) —— Volume Stirrup Ratio of Constraint Stirrups, \( \rho_v = \frac{A_{vol} \sum l_{cc}}{A_{cc} S} \)

\( \rho_s \) —— Longitudinal reinforcement ratio, \( \rho_s = \frac{A_{se}}{A_{cc}} \)

For regional confined concrete beams, the cross-sectional area of the constrained area is \( A_{cc} = b_s x_{cc} \).

The calculation of the bearing capacity of the front section of regional confined concrete should be based on the following basic assumptions:

1. The section should be flat.
2. Does not consider the tensile strength of concrete.
3. Only consider the concrete in the compression zone of the constraint range to participate in the work, and the strength of the constraint body is taken as \( f_{cc} \).

The bearing capacity of the normal section of the bending member shall meet the following requirements:

\[ M \leq b_s x_{cc} f_{ce} h_s' \]  

(11)

\[ b_s x_{cc} f_{ce} \leq A_j f_y \]  

(12)

Assumption: the constraint body is uniformly compressed, assuming that the strength of the constraint body is \( f_{cc} \).

In the above formula:

\( b_s \) —— Constraint width, take the width of the component minus the thickness of the protective layer, \( b_s = b - 2c \).
$x_{cc}$——Constraint height, $\leq 0.45h$;

$f_{cc}$——Compressive strength of restraint, determined by formula (8);

$h'_s$——The distance from the resultant point of longitudinal tension steel bar to the compression center:

$$h'_s = h_0 - c - 0.5x_{cc}$$

(13)

$f_p$——Ordinary steel bar tensile strength;

c——Concrete cover thickness.

Bringing the test data into equations (11) and (12), the theoretical bearing capacity of the regional confined concrete beam is 395.85KN.

3.3. Test phenomenon analysis

The crack distribution and failure form of ordinary reinforced concrete beam are shown in Figure 4. When the load of ordinary reinforced concrete beam reaches 35KN, vertical cracks begin to appear in the middle of the span. When the load reaches 80KN, a lot of vertical cracks appear. When the load reaches 120KN, the vertical cracks in the shear bending section extend to form oblique cracks, and there are oblique cracks in the pure bending section. When the load reaches 150KN, a large number of diagonal cracks are added. When the load reached 240KN, local concrete was crushed at the loading point; the crack width reached 0.2mm. When the load reaches 330KN, a clicking sound is heard, and the crack width reaches 0.3mm, and the displacement changes greatly. When the load reaches 350KN, the concrete of the protective layer under the distribution beam support falls off. When the load reached 370KN, transverse cracks appeared, and the concrete protection layer of the confinement area fell off. Continue to load, the cracks in the middle span continue to expand. When the load reaches 435KN, the concrete in the compression zone of the pure bending section is crushed, the load falls, and the beam is completely destroyed.
According to the experimental phenomenon, we found that before the concrete at the edge of the compression zone is crushed, the regional confined concrete beam has the same force form as the ordinary reinforced concrete super-reinforced beam with the same longitudinal reinforcement. It shows that the confined concrete beam does not play its role before the confined concrete reaches the ultimate compressive strain of the confined concrete beam. After the concrete of the protective layer is crushed, the concrete in the confinement area continues to bear pressure until the confinement body is crushed.

3.4. Analysis of test results

From Table 2 we can see that the error between the theoretical bearing capacity and the experimental bearing capacity of ordinary reinforced concrete beams is within 4%. The error of theoretical bearing capacity and experimental bearing capacity of regional confined concrete beam is 10%. The theoretical calculation value of the regional confined concrete beam is too small. The reason is that the concrete in the compression zone only considers the constrained body to participate in the compression when calculating the theoretical bearing capacity, and ignores the contribution of ordinary concrete in the compression zone to the bearing capacity. The theoretical calculation value of the regional confined concrete beam is too small. The reason is that when calculating the theoretical bearing capacity, the concrete in the compression zone only considers the constrained body to participate in the compression, and ignores the contribution of ordinary concrete in the compression zone to the bearing capacity. But ordinary concrete in the compression zone actually participates in the work when the component is working. Therefore, the bearing capacity of regional confined concrete beams is low. Explain that the calculation formula given by the specification is conservative.

Compared with ordinary reinforced concrete beams with the same longitudinal reinforcement, the bearing capacity of regional confined concrete beams is increased by 24.3%. The protective layer concrete falls off before the regional constrained concrete beams play a role. Explain that the role of the restraint is at the expense of the protective layer. The influence of the loss of concrete strength of the protective layer on the bearing capacity should be considered when designing regional confined concrete.

| Beam                                    | Theoretical capacity(KN) | Test bearing capacity(KN) | Error(%) |
|----------------------------------------|--------------------------|---------------------------|----------|
| Regional confined concrete beam         | 395.85                   | 435                       | 9.9      |
| Ordinary reinforced concrete beam       |                          |                           |          |
| Reinforced beam calculation by limit    | 353.7                    | 350                       | -1.0     |
| Reinforced beam calculation by limit    | 364.7                    | 350                       | -4.0     |

4. Conclusions

Through theoretical analysis and experimental analysis of the bearing capacity of ordinary reinforced
concrete super-reinforced beams and regional confined concrete beams, we found that regional confined concrete beams can effectively improve the flexural bearing capacity of the beam.

① The experimental phenomenon shows that before the concrete is crushed at the edge of the compression zone, the regional confined concrete beam and the ordinary reinforced concrete super-reinforced beam with the same longitudinal reinforcement have the same force form. It shows that the confined concrete beam does not play its role before the confined concrete reaches the ultimate compressive strain of the confined concrete beam.

② According to theoretical and experimental analysis, we found that the flexural bearing capacity of the normal section of confined concrete beams with regional constraints is higher than that of ordinary reinforced concrete beams with the same longitudinal reinforcement.

③ When calculating the bearing capacity of the regional constraint theory, ordinary concrete in the compression zone is not considered in the compression. Its theoretical bearing capacity is low, indicating that the calculation formula given by the code is conservative.

④ The protective layer concrete falls off before the regional constrained concrete beams play a role. Explain that the role of the restraint is at the expense of the protective layer. The influence of the loss of concrete strength of the protective layer on the bearing capacity should be considered when designing regional confined concrete.

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