Theoretical Calculation of Flexural Load Capacity of RC Beams Reinforced with Aluminum Alloy -ECC Composites

Chunmei Mo[1], Jun Huang[1, *], Junzhong Huang[2]

[1]College of Architecture and Civil Engineering, Nanning University, Nanning 530200, P. R. China

[2]Guangxi Construction Engineering Group No.4 Construction Engineering Co. LTD, Guilin 541000, P. R. China

* Corresponding Author Email: huangjun@nnxy.edu.cn

Abstract. In order to study the flexural performance of RC beams reinforced with aluminum alloy-ECC composites under different damage modes and to improve the theoretical method of calculating their flexural ultimate bearing capacity, the formula for the ultimate flexural bearing capacity of concrete beams reinforced with aluminum alloy tendons under two different damage modes of aluminum alloy tendons pulling off and concrete crushing in the compression zone was derived based on the intrinsic relationship of concrete in the compression zone, and the formula for the ultimate bending bearing capacity of concrete beams reinforced with aluminum alloy tendons and ECC composites under different reinforcing modes was calculated. The ultimate bearing capacity of concrete beams under different reinforcement modes was calculated, and the finite element analysis of the flexural performance of the reinforced beams was carried out at the same time, and the theoretical values were compared with the results of finite element simulation and the existing test values to verify the correctness of the formulae. The results show that the theoretical calculated values of RC beams reinforced with aluminum alloy -ECC composites are in good agreement with the results of finite element analysis and test values, and the accuracy of the theoretical calculations is high, and the formulae derived can effectively avoid the problems that are unfavorable to the practical application of engineering due to the excessive complexity of theoretical calculations, and the relevant calculation methods are of certain reference value for guiding the design of RC beams reinforced in actual projects.

Keywords: Aluminum alloy bars, ECC. RC beams. Ultimate flexural capacity.

1. Introduction

Reinforced concrete beams are important bending members of building structures, and the bearing capacity and durability of reinforced concrete beams will gradually decrease with the passage of time and under the action of external loads of building structures. Therefore, it is extremely important for reinforced concrete beams to be strengthened and reinforced to improve or restore their load carrying capacity to the performance of the whole building structure. Aluminum alloy material is stronger than steel, and the density is only 1/3 of steel, and has the advantages of good ductility and corrosion resistance, has been widely studied and applied in the field of reinforcement and repair of building structures [1-4].

Yang et al. [5] pasted the aluminum alloy plate on the bottom of the beam, and investigated the load carrying capacity of RC beams reinforced with aluminum alloy plate in different connection forms through tests, which showed that the load carrying capacity of the reinforced beams with different connection forms were significantly improved, and at the same time, the reinforced RC beams had a good ductility and energy-consuming capacity. Xing et al.[6] used embedded method to embed prestressed aluminum alloy tendons into the bottom of reinforced concrete beams, and carried out bending static load tests on the reinforced beams to study the effects of the amount of aluminum alloy reinforcement, prestressing, and prestressing level on the bending damage modes and crack characteristics of the reinforced beams, and the study showed that the embedded reinforcing method of aluminum alloy tendons can significantly increase the load carrying capacity of the concrete beams, and that the pre-stressing, increasing the amount of reinforcement, and increasing the prestressing, increasing the amount of reinforcement and increasing the level of prestressing can all effectively control the crack extension.

Engineered cementitious composites (ECC) have ultra-high toughness and can provide sufficient bond when reinforcing, which can solve the problem of poor durability performance of organic interface paste, and can effectively inhibit beam cracking [7-8]. Deng et al.[9] studyed fiber reinforced composite (FRP) mesh and engineering cementitious composite (ECC) composite reinforcement on the deflection of reinforced concrete beams, the study showed that FRP mesh-ECC composite reinforcement can significantly improve the test beam ultimate load carrying capacity and flexural stiffness, beams and the interface of the ECC material abrasive treatment of the reinforcing layer interfacial adhesion can improve the performance of better. Qian et al.[10] used SMA and ECC composite materials to reinforce the beams for flexural performance, and the study showed that the SMA/ECC composite reinforced beams not only improved the load carrying capacity, and have better ductility and deformation capacity, while having superior self-repair performance.

Currently, many scholars have carried out a large number of derivation studies in the theoretical calculation of flexural concrete members. Pan et al.[11] established an improved calculation model for the flexural performance of reinforced concrete beams reinforced with carbon fiber reinforced composite mesh and polymer cement mortar composite reinforcement on the basis of experimental study, taking into account the peeling strain. Fang Sheng et al.[12] derived the formula for calculating the flexural capacity of FRP-reinforced concrete beams under three different damage modes, taking into account factors such as the influence of secondary forces and hysteretic strain effects. Li et al.[13] used high-strength strand mesh and cementitious composites for flexural reinforcement of reinforced concrete beams, and proposed the formula for calculating the bending capacity of damage-free RC beams reinforced with ECC by high-strength strand mesh on the basis of experimental results. Gao et al.[14] proposed a model for calculating the bending capacity of reinforced concrete beams reinforced with prestressed carbon fiber cloth based on the consideration of prestressing loss.

However, there are fewer studies on the derivation of theoretical formulas for the flexural load capacity of reinforced concrete beams reinforced by aluminum alloy bar-ECC composites. In this paper, the reinforcing method was to use ECC material as the reinforcing layer at the bottom of reinforced concrete beams and embed aluminum alloy bar into ECC to form a composite material for structural reinforcement, to derive the formulae for the ultimate flexural capacity of the reinforced concrete beams reinforced by aluminum alloy bar pulling off and the crushing of concrete in compression zone under the two different damage modes, and to calculate the ultimate load capacity of the concrete beams under the different reinforcement modes, and meanwhile, finite element analysis was carried out to analyze the bending performance of the reinforced beams.

2. Theoretical calculation method of flexural capacity of beams reinforced with aluminum alloy bars-ECC composites in positive section

2.1. Model of reinforced beam

The reinforcement method used in this paper was to use ECC material as the reinforcement layer at the bottom of the beam, and the 7075 high-strength aluminum alloy will be in the form of reinforcement bars, and the embedded reinforcement method will be used to embed the aluminum alloy bars into the ECC reinforcement layer to achieve the effect of composite reinforcement of reinforced concrete beams. The specific reinforcement model schematic diagram is shown in Figure 1.

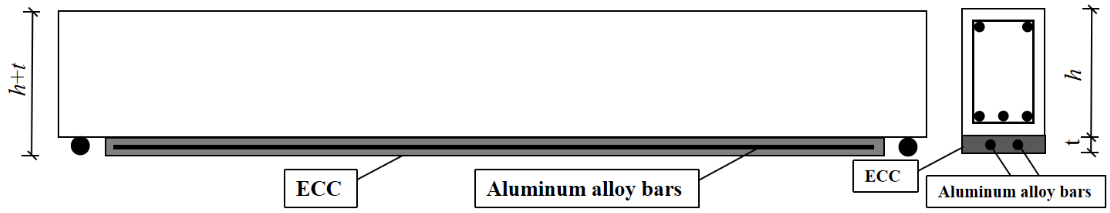

Fig. 1 Aluminum reinforcement-ECC composite reinforced concrete beams

2.2. Damage modes

Experimental studies [15-16] showed that, under the condition of effective anchorage measures, the bending damage modes of aluminum alloy bar-ECC composite reinforced beams were as follows: concrete crushing in the compression zone, pulling off of aluminum alloy bar, and bond failure between ECC and concrete at the bottom of the beam, which was related to factors such as thickness of the adhesive, strength of the concrete, quality of construction, and reliability of anchorage measures. Reliable anchorage measures and other factors, can be taken in the process of strengthening special measures to be avoided, so this paper did not consider this damage mode in the analysis process, the main analysis of the compression zone concrete crushing, aluminum alloy bar pull off these two damage modes.

2.3. Basic assumptions

(1) The beam before and after reinforcement conforms to the flat section assumption, and the role of concrete in tensile zone was not considered after concrete cracking.

(2) Concrete compression stress-strain relationship to calculate the initial tensile strain at the bottom of the beam, the tensile reinforcement of the beam was generally not yielded, which can be simplified to a triangular distribution, and the stress-strain relationship of the reinforcement was taken according to (GB50010-2010) [17].

(3) Aluminum alloy bar according to the line elasticity relationship to determine its stress-strain relationship until the destruction.

(4) Aluminum alloy bar and concrete had no relative slip and no bond damage.

2.4. Ontological relationships of materials

(1) Stress-strain relationships for concrete were based on equations recommended in concrete design codes:

$$\sigma_c = \begin{cases} f_c\left[2\dfrac{\varepsilon_c}{\varepsilon_0} - \left(\dfrac{\varepsilon_c}{\varepsilon_0}\right)^2\right], & 0 < \varepsilon_c \le \varepsilon_0 \\ f_c, & \varepsilon_0 < \varepsilon_c \le \varepsilon_{cu} \end{cases} \tag{1}$$

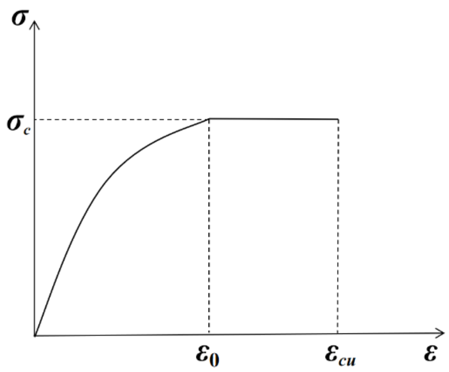

Fig. 2 Concrete stress-strain relationship

The Ramberg-Osgood model has been widely used in the study of the intrinsic structure relationship of metal structures, and the modified Ramberg-Osgood model was used for aluminum alloy tendons in the paper[21]:

$$\varepsilon = \frac{\sigma}{68000} + 0.002\left(\frac{\sigma}{f_{0.2}}\right)^{0.1 f_{0.2}} \tag{2}$$

The ECC uniaxial stretching principal structure was expressed using a simplified bilinear model [18] as shown in Fig. 3:

$$\sigma_t = \begin{cases} \dfrac{\sigma_{tc}}{\varepsilon_{tc}}\varepsilon_t & ,0 \le \varepsilon_t \le \varepsilon_{tc} \\ \sigma_{tc} + \dfrac{\sigma_{tu} - \sigma_{tc}}{\varepsilon_{tu} - \varepsilon_{tc}}\left(\varepsilon_t - \varepsilon_{tc}\right) & ,\varepsilon_{tc} \le \varepsilon_t \le \varepsilon_{tu} \end{cases} \tag{3}$$

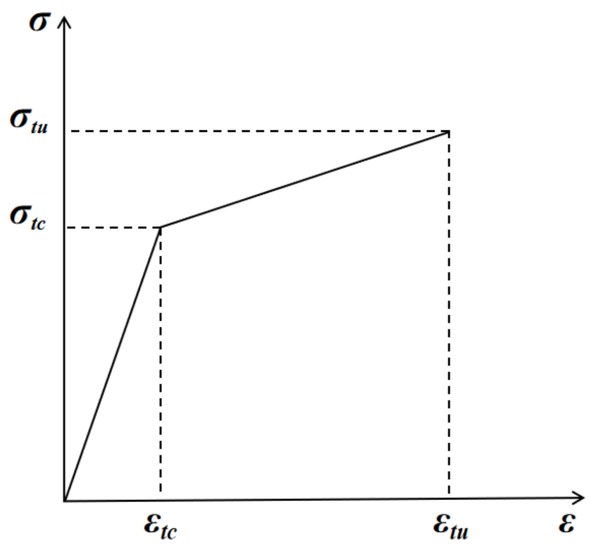

Fig. 3 Tensile principal structure of ECC material

2.5. Calculation of Ultimate Flexural Load Capacity of Aluminum Alloy Bars-ECC Composite Reinforced Beams under Different Damage Modes

Due to the reinforced beam compression zone of the erection of the steel was configured according to the structural requirements, its impact on the bending capacity of the section was not significant, in the calculation can be ignored, the text of the single-bar rectangular section beams according to the derivation of the formula of the bending capacity of the cross-section, respectively, the establishment of aluminum alloy tendons pulling off the compression zone of the concrete crushing the two types of beams of the bending damage modes of the bending bearing capacity calculation model.

According to the flat section assumption, the strain distribution of the reinforced beam section was shown in Fig. 4. According to the intrinsic relationship of ECC material, it can be seen that the ECC material after cracking can still continue to work, and the stress-strain increases linearly when it was within a certain range, so the geometric relationship between the tensile stress and the ultimate tensile stress of the ECC material was obtained as follows:

$$\sigma_{\mathrm{t}} = \frac{(h - x_0)\sigma_{\mathrm{Eu}}}{h + t - x_0} \tag{4}$$

Where: h, t, x_0, σ_{Eu} - beam height, ECC layer thickness, theoretical height of compressed zone, and ultimate tensile stress of ECC material.

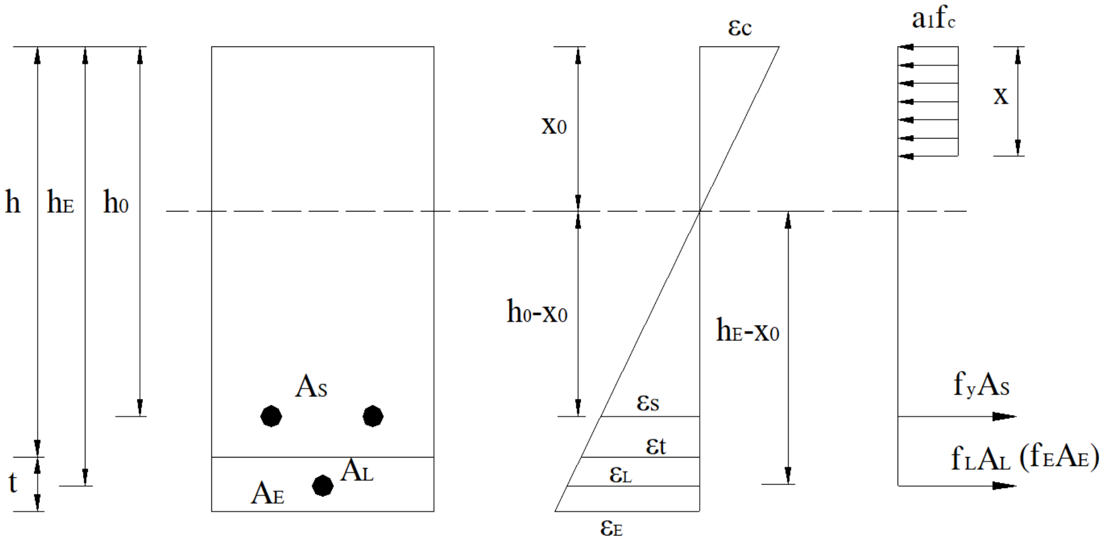

Fig. 4 Stress-strain distribution of ECC-alloy reinforced beam section

(1) Damage mode 1: aluminum alloy bar pulling off

When the bending damage mode of aluminum alloy bar pull-off occurs, after the stress-strain diagram of the reinforced beam was equated, the tensile strain length of the ECC part was substituted into Eq. (4), and Eq. becomes:

$$\frac{1}{2}\left(\sigma_{\mathrm{Eu}}+\sigma_{\mathrm{t}}\right)=\sigma_{\mathrm{tu}}-\frac{\sigma_{\mathrm{Eu}}\mathrm{t}}{2\left(h+t-x_0\right)} \tag{5}$$

According to the equilibrium relationship of forces in the horizontal direction, we get:

$$\alpha_1 f_{\mathrm{c}}bx = f_{\mathrm{y}}A_{\mathrm{s}} + f_{l\mathrm{u}}A_l + bt\left[\sigma_{\mathrm{Eu}}-\frac{\sigma_{\mathrm{Eu}}\mathrm{t}}{2\left(h+t-x_0\right)}\right] \tag{6}$$

Where: f_{c}, f_{y}, f_{lu} - concrete compressive strength, steel yield strength, aluminum alloy bar ultimate tensile strength; A_{s}, A_l - tensile steel cross-sectional area, aluminum alloy bar cross-sectional area; b - beam cross-sectional width; x -concrete equivalent compressive zone height ($x=\beta_1 x_0$); according to the Concrete Design Code, take $\alpha_1=1.00$ $\beta_1=0.80$.

After finding the value x, the bending capacity can be determined according to the following formula:

$$M_{\mathrm{u}} = f_{\mathrm{y}}A_{\mathrm{s}}\left(h_0-\frac{x}{2}\right)+f_{l\mathrm{u}}A_l\left(h_E-\frac{x}{2}\right)+bt\left[\sigma_{\mathrm{Eu}}-\frac{\sigma_{\mathrm{Eu}}\mathrm{t}}{2\left(h+t-x_0\right)}\right]\left(h_E-\frac{x}{2}\right) \tag{7}$$

Where: h_0, h_{E} -the effective height of the section, the distance from the point of combined action of aluminum alloy reinforcement or ECC reinforcement layer to the top of the beam.

(2) Damage mode II: concrete crushing damage in compression zone

When the concrete was crushed by the pressure area, at this time the strain in the concrete pressure area reached ε_{cu}, by the horizontal direction of the force equilibrium conditions obtained:

$$\alpha_1 f_{\mathrm{c}}bx = f_{\mathrm{y}}A_{\mathrm{s}} + f_l A_l + btf_{\mathrm{E}} \tag{8}$$

f_l, f_E Which can be calculated in the following formula:

$$f_l = E_l\varepsilon_{cu}\left(\frac{\beta_1 h_E}{x}-1\right) \tag{9}$$

$$f_E = E_E \varepsilon_{cu}\left(\frac{\beta_1 h_E}{x} - 1\right) \tag{10}$$

Where: E_l , E_E - modulus of elasticity of aluminum alloy reinforcement and ECC material.

After finding the value x , the bending capacity can be determined by the following formula:

$$M_u = \alpha_1 f_c bx\left(h_E - \frac{x}{2}\right) - f_y A_s\left(h_E - h_0\right) \tag{11}$$

3. Example and Verification

3.1. Finite element analysis of ultimate flexural capacity of RC beams reinforced with aluminum alloy bar-ECC composites

The article establishes the finite element model of reinforced reinforced concrete beams, compares the results with the test beams in the literature [9], verifies the correctness of the model, and prepares for the later comparative analysis of the finite element analysis results with the theoretical values. Reinforced beam related materials and dimensions were adopted from literature [9], the concrete strength grade of the test beam JB-9 was C30, the length of the beam was 1800 mm, the cross-section size was b×h=150mm×250 mm, the tensile reinforcement of the beam was 2C10, the compression reinforcement was 2C8, the hoop reinforcement was C8@100,, and the thickness of the protective layer of the concrete was 25 mm. the details of the mechanical properties of the ECC materials and aluminum alloy tendons were shown in Table 1-2.

Table 1. Mechanical properties of ECC[9]

Material	Compressive strength /MPa	Crackingstrength /MPa
ECC	28.6	3.6

Table 2. Mechanical properties of aluminum alloy bars

Material	Yield strength/MPa	Ultimate strength/MPa	Elastic modulus/GPa
Aluminum alloy bars	528.4	589.7	72.7

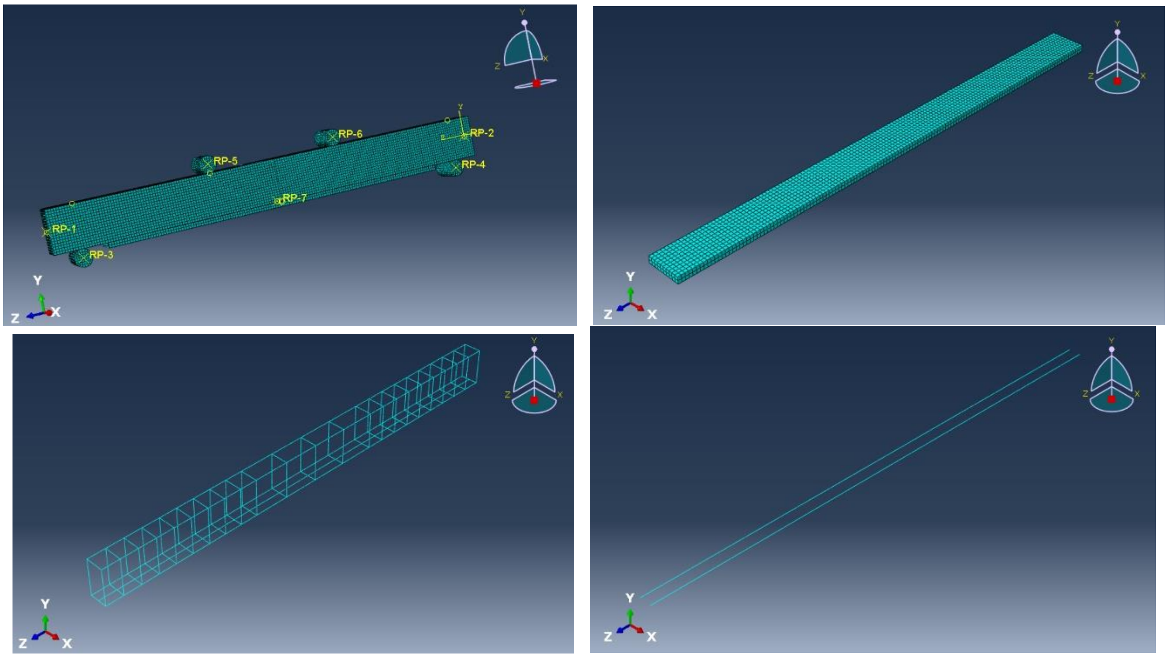

Fig. 5 Finite element model and assembly diagram of reinforcement beam components

3.2. Finite element analysis and verification of test results

Finite element simulation of the reinforced concrete beam test beam JB-9 was carried out to verify the agreement between the simulated and tested values. The simulation results were compared with the test results to verify the scientific validity of the model, and the simulation results were shown in Table 3.

Table 3. Comparison of tested and simulated values of JB-9 beams

Data name	Experimental value[9]	Finite element results	Inaccuracies
Yield load/kN	79	84.84	7.39%
Yield deflection/mm	4.7	4.98	5.96%
Ultimate load/kN	90	97.85	8.72%
Ultimate deflection/mm	22.94	24.26	5.75%

According to the above data, it can be seen that the simulation results of the reinforced beams were basically consistent with the test results, and the simulation results were larger than the test results, which was due to the fact that the reinforcement bars had bond slip during the loading process during the test process, and the finite element modeling was used to simulate the interaction between the reinforcement bars and the concrete in the way of built-in region, and did not take into account the role of reinforcement bar slipping, so the beam stiffness in the finite element model was larger than that in the test beams. Therefore, the beam stiffness of the finite element model was larger than that of the test beam. The errors between the cracking load and damage load of the experimental beams analyzed by finite element analysis and the experimental values were controlled within 10%, which was permissible for numerical simulation. The finite element analysis better reflects the stress state of the experimental beams, which proves the feasibility and accuracy of the finite element model.

3.3. Verification of theoretical values of flexural capacity of reinforced beams

On the basis of the above finite element model, the formula for the flexural capacity of the reinforced beams with aluminum alloy-ECC composite material was further verified. The beams designed with different reinforcement methods were shown in Table 4.

Table 4. Design table for beams with different types of reinforcement

Test piece number	ECC layer(mm)	Diameter of aluminum bar(mm)	Aluminum alloy bars
L-E30	30	None	None
L-E30-A	30	12	1
L-E30-B	30	12	2
L-E35	35	None	None
L-E35-A	35	12	1
L-E35-B	35	12	2
L-E40	40	None	None
L-E40-A	40	12	1

The theoretical formula and finite element method were used to calculate the ultimate bearing capacity of the reinforced beams respectively, and the theoretical values were summarized and compared with the simulated values to verify the correctness of the bearing capacity formula, and the comparison was shown in Table 5.

Table 5. Comparison of theoretical values and finite element results

Test piece number	Theoretical calculation results(kN)	Finite element analysis results(kN)	Specific value
L-E30	84.79	91.81	0.924
L-E30-A	144.16	154.62	0.932
L-E30-B	199.09	210.28	0.947
L-E35	88.1	94.36	0.934
L-E35-A	147.47	158.62	0.930
L-E35-B	202.2	214.57	0.942
L-E40	92.29	97.85	0.943
L-E40-A	150.78	164.27	0.918
Mean			0.934
Standard deviation			0.0094
Coefficient of variation			0.0101

The mean, standard deviation and coefficient of variation of the ratio of the theoretical value of the ultimate flexural capacity of the reinforced beams calculated in the article to the finite element analysis results were 0.934, 0.934 and 0.0101, and the finite element analysis ultimate capacity of the reinforced beams were all larger than the theoretical value, but the difference values were all less than 9%, and a small amount of the difference may be due to the fact that the tensile reinforcement beams were neglected in the establishment of the formula for calculating the flexural load capacity. The contribution of the uncracked part of the concrete to the tension bearing. The results of the flexural bearing capacity calculation formula for reinforced concrete beams reinforced with aluminum alloy bars-ECC composites were in good agreement with the finite element results, which verifies the correctness of the model and was suitable for calculating the flexural bearing capacity of such reinforced beams in the normal section.

4. Conclusion

(1) The theoretical formula of ultimate flexural capacity of RC beams reinforced with aluminum alloy bars-ECC composites deduced in this paper was based on the uniaxial compressive stress-strain curve of concrete recommended by the concrete design code, and through a few reasonable basic assumptions, it can avoid the problem that the theoretical calculations were too complicated and not conducive to the practical application of the project, and at the same time, it ensured the accuracy of the theoretical calculations.

(2) The theoretical formula of ultimate flexural load capacity of RC beams reinforced with aluminum alloy bar-ECC composites derived in this paper was used to calculate the ultimate load capacity of RC beams under different reinforcing methods, and the results obtained were more in line with the experimental results and the finite element analysis results, and were in line with the requirements of engineering accuracy.

(3) This paper provided a calculation idea, the derivation of the formula was not limited to ECC materials and aluminum alloy bar reinforced beams bearing capacity calculation, the use of other reinforcing layer materials and carbon fiber reinforcement materials composite reinforced beams were also applicable.

Acknowledgments

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