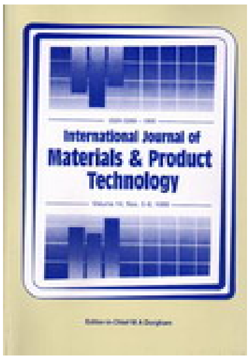

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Calculation method for ultimate bearing capacity of reinforced concrete beams based on unified strength theory

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Abstract: In order to improve the accuracy and reliability of the calculation results of the ultimate bearing capacity of reinforced concrete beams, this paper proposes a calculation method for the ultimate bearing capacity of reinforced concrete beams based on the unified strength theory. Firstly, we analyse the mechanical properties of reinforced concrete materials and conduct principal stress analysis of reinforced concrete beams. Then, the plastic damage model (CDP model) is used to simulate the mechanical properties of concrete components under reciprocating loads. Based on the unified strength theory assumption, concrete and steel bars are considered as equivalent materials, and the shear deformation method is used to calculate the ultimate bearing capacity. The results show that the accuracy of the proposed method can reach up to 99.2%, indicating that the proposed method can effectively improve the accuracy of calculating the ultimate bearing capacity of reinforced concrete beams.

Keywords: force model; reinforced concrete beams; shear deformation method; stress distribution; yield strength.

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1 Introduction

The study of the calculation method for the ultimate bearing capacity of reinforced concrete beams can help people better understand and grasp the stress characteristics of building structures, thereby promoting innovation and development of building structural technology, achieving safer and more economical performance. Its seismic resistance is crucial for earthquake disaster prevention. Research on the calculation method of ultimate bearing capacity of reinforced concrete beams (Liu, 2021; Zhang and Yang, 2021; Wu and Zhong, 2022). Steel tube concrete has the advantages of high bearing capacity, convenient construction, and good fire resistance, and has been widely used in the construction of high-rise and super high-rise buildings and large-span arch bridges (Zhang and Yang, 2021; Peng et al., 2022). In recent years, domestic and foreign scholars have achieved many achievements in the research on the bearing capacity of steel tube concrete.

Yu et al. (2021) propose an uncertain analysis of the calculation mode for the shear bearing capacity of reinforced concrete beams, and calculates the shear span ratio based on the geometric dimensions of the beam. Determine the shear failure mode of the beam based on the shear span ratio, and determine the effective shear failure area on the beam section based on the shear failure mode. Calculate the shear bearing capacity of concrete based on the shear failure area of the section and the shear strength of the concrete. Calculate the shear bearing capacity of the steel reinforcement based on the cross-sectional shear failure area, reinforcement ratio, and shear strength of the steel reinforcement. Based on the shear bearing capacity of concrete and steel bars, and considering the contributions of both, the total shear bearing capacity of the beam is calculated. This method can effectively improve the accuracy of shear bearing capacity of reinforced concrete beams, but the calculation takes a long time. Tuo et al. (2022) propose a Bayesian theory based model for predicting the shear bearing capacity of reinforced recycled concrete beams, and collects data related to research objectives, including material properties, geometric dimensions, and experimental data of reinforced recycled concrete beams. Based on Bayesian theory, a formula for calculating the compressive strength of core concrete in steel pipes was derived. A shear bearing capacity calculation model for reinforced recycled concrete beams was established considering concrete strength, steel reinforcement ratio, and beam geometry, and a formula for calculating the ultimate bearing capacity of steel pipe concrete was constructed. Estimate the parameters in the model through Bayesian analysis. This method can effectively improve the effectiveness of shear bearing capacity of reinforced concrete beams, but the robustness of the calculation results is poor. Yan (2022) proposes a finite element analysis of the shear bearing capacity of reinforced concrete beams based on the pressure path method, considering the stress-strain relationship between concrete and steel during the stress process, and considering the influence of factors such as shear span ratio and reinforcement ratio on the shear bearing capacity of the beam. Based on the pressure path method, a calculation model for the shear bearing capacity of reinforced concrete beams is established. The maximum likelihood estimation method is used to estimate the parameters in the model, and other experimental data or field observation data are used to verify the established model. Evaluate the accuracy and reliability of the model by comparing the calculated results with the actual observation results. This method can effectively improve the efficiency of shear bearing capacity of reinforced concrete beams, but the calculation accuracy is poor.

In response to the problems of poor calculation accuracy and long calculation time in the above methods, this article introduces the unified strength theory to calculate the ultimate bearing capacity of reinforced concrete beams. The specific research ideas are as follows:

First, the mechanical properties of concrete and steel are analysed to determine the strength parameters of concrete and steel.

Secondly, tensile tests are used to determine the tensile strength and shear yield limit of reinforced concrete beams, and the principal stress analysis of reinforced concrete beams is carried out using the unified strength theory.

Then, the plastic damage model (CDP model) is used to simulate the mechanical properties of reinforced concrete components under reciprocating loads. Based on the assumption of the unified strength theory, concrete and steel bars are considered as equivalent materials, and the shear deformation method is used to calculate the ultimate bearing capacity of reinforced concrete beams.

Finally, experimental verification was conducted using the accuracy index for calculating the ultimate bearing capacity of reinforced concrete beams, and conclusions were drawn.

2 Calculation of ultimate bearing capacity of reinforced concrete beams based on unified strength theory

2.1 Mechanical properties of materials

2.1.1 Mechanical properties of concrete

The test used specimens poured from the same batch of C25 commercial concrete, and six standard cubic test blocks were reserved as the basic performance of the material during pouring. The test blocks and specimens were cured under the same conditions. After 30 days of curing, axial compression tests were conducted on the test blocks according to the method of GB50010-2010. The test equipment used in this test was the RMT-201 testing machine, which used a displacement controlled loading system, The average compressive strength of the cube measured is 31.97 MPa. According to the specifications, the standard compressive strength values of the concrete cube are $f_{cu,k}$, the axial compressive strength is $f_{c,k}$, the axial tensile strength is $f_{t,k}$, and the elastic modulus is E_c. The calculation formula is as follows:

$$f_{cu,k} = f_{cu,m} - 1.645\sigma \tag{1}$$

$$f_{c,k} = 0.88\alpha_1\alpha_2 f_{cu,k} \tag{2}$$

$$f_{t,k} = 0.88\times 0.395 f_{cu,k}^{0.55} \tag{3}$$

$$E_c = \frac{10^5}{2.2 + \dfrac{34.7}{f_{cu,k}}} \tag{4}$$

For C25 concrete, take 0.76 for 11, without considering the reduction factor, and take α_1 for α_2. The results of all parameters calculated are shown in Table 1.

Table 1 Mechanical properties of concrete

$f_{cu,m}$/MPa	$f_{cu,k}$/MPa	$f_{c,k}$/MPa	$f_{t,k}$/MPa	E_c/MPa
31.97	25.64	17.15	2.08	2.8×10^4

2.1.2 Mechanical properties of steel

The steel bars for the test opening beam are from the same batch of steel, with a grade of HRB400E. The 100 TB screen display hydraulic universal material testing machine was used in this test, using a force controlled loading system and referring to GB/T228-2002 for testing. The parameters of the obtained material properties test results are shown in Figure 1.

Table 2 Mechanical property indicators of steel

Diameter/mm	*Level*	*Yield strength* f_y/MPa	*Strength* f_u/MPa	*Elastic modulus E/GPa*	*Elongation rate δ/%*
10	HRB400	452.13	655.54	197.13	12.88
12	HRB400	459.23	646.99	194.22	16.92
16	HRB400	406.14	583.87	203.89	15.87

Figure 1 Strength of materials performance test, (a) mechanical property test of concrete (b) mechanical properties test of steel (see online version for colours)

(a) (b)

2.2 Principal stress analysis of concrete beams based on unified strength theory

Using the double shear element as the mechanical model, considering all stress components acting on the double shear element and their different effects on material failure, a unified strength theory is established. This section uses the basic mechanical performance tests of reinforced concrete beams to determine the tensile and compressive strength difference effect, intermediate principal stress effect parameters, and ultimate principal stress analysis of reinforced concrete beams based on unified strength.

2.2.1 Theoretical parameters of material strength α and b

According to a large amount of data at home and abroad, the strength of materials under complex stress states has some of the most basic characteristics, with the tensile compressive strength difference effect and intermediate principal stress effect being the most prominent. The tensile compressive strength difference effect refers to the unequal or even significant difference between the compressive strength and compressive strength of a material. Therefore, a unified strength theory for describing such materials requires two strength parameters. The parameter α in material strength theory usually refers to the ratio between the compressive strength and torsional strength of α material. It specifically represents the magnitude of the material's torsional resistance relative to its compressive strength. This parameter is mainly used to describe the performance of the material under torsional loading. Among them, a larger α value indicates a higher compressive strength of the material, while a smaller α value indicates a higher torsional strength of the material. The difference in tensile and compressive strength should be measured using α methods, and the shear strength of α should be calculated using the following formula:

$$\alpha = \frac{f_t}{f_c} \tag{1}$$

In the formula, f_t is the uniaxial tensile strength of the material, in MPa; f_c is the uniaxial compressive strength of the material, in MPa.

The intermediate principal stress effect refers to the influence of intermediate principal stress σ_2 on strength. Numerous experiments and studies have shown that the intermediate principal stress has a certain impact on the strength of materials, especially brittle materials such as rock and concrete. The magnitude of b is used to reflect this degree of influence, and b is the coefficient reflecting the influence of intermediate principal shear stress, which is related to the shear yield limit τ_b and uniaxial tensile strength f_s of the material.

Table 3 Theoretical parameters of specimen strength α and b

Group	*Parameter α*	*Parameter b*
B05	0.10	0.51
B06	0.11	0.53
B07	0.09	0.52

The intermediate principal stress effect should be measured using b, and b. The intermediate principal stress effect should be calculated using the following formula:

$$b = \frac{(1+\alpha)\tau_b - f_s}{f_s - \tau_b} \tag{2}$$

For most commonly used materials in engineering, their tensile strength limit and shear yield limit are difficult to determine; This article uses tensile tests to obtain the tensile strength and shear yield limit of reinforced concrete beams, which are $\tau_b = 0.85\tau$. For the current application of reinforced concrete beam materials by the research group, this article calculates the values of parameters α and b that affect material strength based on experiments, as shown in Table 3.

2.2.2 Expression of unified strength principle principal stress for materials

The unified strength theory is defined as: when two large principal shear stresses acting on a unit and the corresponding normal stress influence function reach a certain extreme value, the material undergoes failure. The expression of the principal stress in the unified strength theory is:

$$F = \sigma_1 - \frac{\alpha}{1+b}(b\sigma_2 + \sigma_3) \qquad 当\sigma_2 \le \frac{\sigma_1 + a\sigma_3}{1+\alpha}时 \tag{3}$$

$$F' = \frac{1}{1+b}(\sigma_1 + b\sigma_2) - a\sigma_3 \qquad 当\sigma_2 \ge \frac{\sigma_1 + a\sigma_3}{1+\alpha}时 \tag{4}$$

Considering the research and experience in Table 3 and relevant literature, this paper gives the strength parameters $\alpha = 0.1$ and $b = 0.5$ that affect the strength of autoclaved aerated concrete blocks. Substituting α and b into formulas (3) and (4), the expression for the principal stress of reinforced concrete beams based on the unified strength theory is obtained as follows:

$$F = \sigma_1 - \frac{\sigma_2 + 2\sigma_3}{30} \qquad 当\sigma_2 \le \frac{10\sigma_1 + \sigma_3}{11}时 \tag{5}$$

$$F' = \frac{2\sigma_1 + \sigma_2}{3} - \frac{\sigma_3}{10} \qquad 当\sigma_2 \ge \frac{10\sigma_1 + \sigma_3}{11}时 \tag{6}$$

Complete the main stress analysis of the concrete beam.

2.3 Constitutive model construction of reinforced concrete beams

The material constitutive model is an equation that mathematically expresses the inherent mechanical properties of a material. In the unified strength theory, selecting an appropriate material constitutive model can ensure accurate simulation results while also considering high computational efficiency. Therefore, this section will provide a detailed introduction to the selection method of the constitutive model of reinforced concrete beams in the unified strength theory of the new type of external hoop joints.

2.3.1 Constitutive model of concrete

The unified strength theory incorporates three constitutive models for concrete materials, namely the dispersion cracking model, brittle cracking model, and plastic damage model. The dispersion cracking model disperses cracks in concrete components and cannot be used to simulate concrete components that produce large cracks at the macro level. The brittle cracking model of concrete is commonly used to simulate concrete components mainly subjected to tensile failure, but it is also not applicable to the simulation of new types of external hoop joint concrete components under reciprocating loads. The plastic damage model (CDP model) simulates the stiffness degradation phenomenon of concrete caused by the accumulation of failure during the loading process through damage factors, and allows users to define the uniaxial stress-strain relationship of concrete to characterise the inelastic behaviour of concrete. Therefore, this article selects the CDP model to simulate the mechanical properties of reinforced concrete components under reciprocating loads.

2.3.1.1 Stress-strain relationship of concrete under uniaxial compression and tension

The CDP model assumes that the damage of concrete is composed of tensile cracking and compressive failure of the material, and the material failure process is controlled by tensile equivalent plastic strain and compressive equivalent plastic strain, respectively. In addition, the CDP model indirectly simulates the bond slip effect between steel bars and concrete by defining cracking strain and nonlinear elastic strain.

After inputting numerical values, the unified strength theory automatically converts the two into corresponding equivalent plastic strains to complete the description of the concrete plastic damage model. The relationship between the above parameters and the stress-strain curve of concrete under uniaxial compression is shown in Figure 2, and the specific conversion method is shown in equations (7)–(10).

$$\sigma_c = (1-d_c)E_0\left(\varepsilon_c - \tilde{\varepsilon}_c^{pl}\right) \tag{7}$$

$$\sigma_t = (1-d_t)E_0\left(\varepsilon_t - \tilde{\varepsilon}_t^{pl}\right) \tag{8}$$

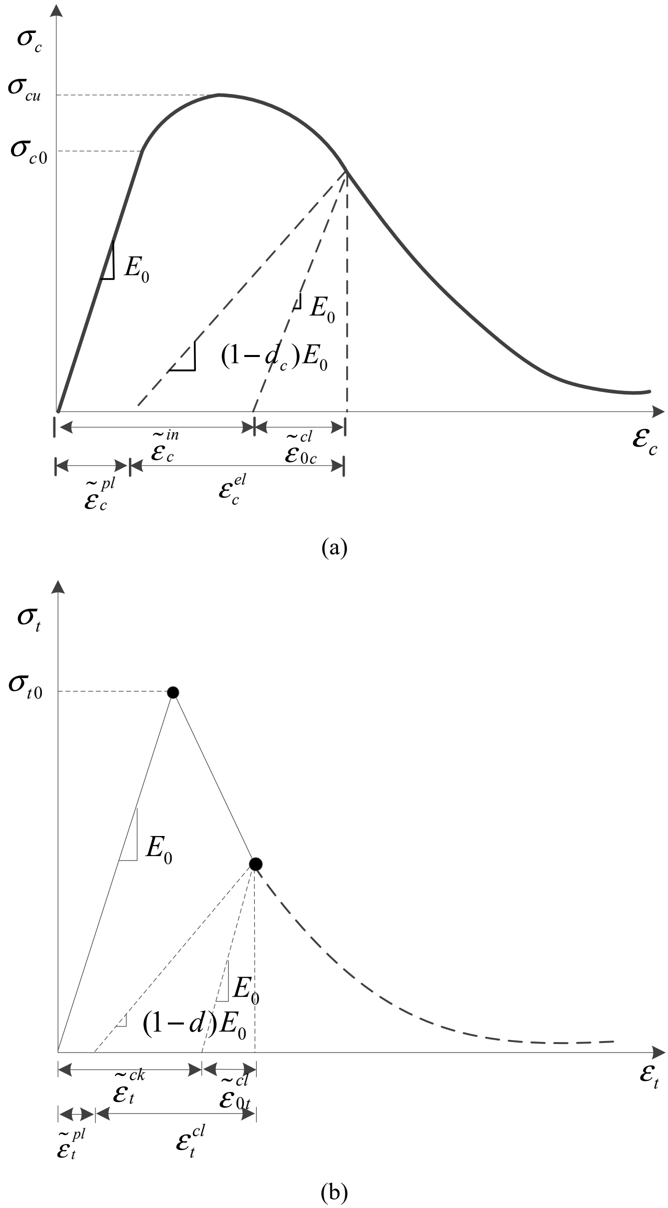
$$\tilde{\varepsilon}_c^{pl} = \tilde{\varepsilon}_c^{in} - \frac{d_c}{(1-d_c)}\frac{\sigma_c}{E_0} \tag{9}$$

$$\tilde{\varepsilon}_t^{pl} = \tilde{\varepsilon}_t^{ck} - \frac{d_t}{(1-d_t)}\frac{\sigma_t}{E_0} \tag{10}$$

In the equation, d_c and d_t are the compression and tension damage factors, respectively. The calculation method is shown in equations (11) and (12).

$\tilde{\varepsilon}_c^{in}$, $\tilde{\varepsilon}_t^{ck}$ represents non-elastic strain and cracking strain, while E_0 represents the elastic modulus of concrete.

Figure 2 Stress-strain curve of concrete, (a) stress-strain curve under uniaxial compression (b) stress-strain curve under uniaxial tension



2.3.1.2 Determination of damage factors

The CDP model simulates the phenomenon of stiffness degradation of concrete materials under reciprocating loads using a damage factor of 55. The specific calculation methods for compression and tensile damage factors d_c and d_t in this paper are shown in equations (11)–(14):

$$d_c = \frac{(1-\eta_c)\tilde{\varepsilon}_c^{in} E_0}{\sigma_c + (1-\eta_c)\tilde{\varepsilon}_c^{in} E_0} \tag{11}$$

$$d_t = \frac{(1-\eta_t)\tilde{\varepsilon}_t^{ck} E_0}{\sigma_c + (1-\eta_t)\tilde{\varepsilon}_t^{ck} E_0} \tag{12}$$

$$\tilde{\varepsilon}_c^{in} = \varepsilon_c - \frac{\sigma_c}{E_0} \tag{13}$$

$$\tilde{\varepsilon}_t^{in} = \varepsilon_t - \frac{\sigma_t}{E_0} \tag{14}$$

In the equation, η_t and η_c represent the ratio of plastic strain to inelastic strain under tension and compression, taking 0.9 and 0.6, respectively. σ_t, ε_t represents the uniaxial tensile stress and strain values of concrete. σ_c, ε_c represents the stress and strain values of concrete under uniaxial compression.

2.3.1.3 Stress-strain relationship of concrete under uniaxial cyclic loading

The stress-strain relationship of concrete under uniaxial cyclic load, and the specific calculation method is shown in equation (15). Equation d is a functional relationship related to the material stress direction state factor (s_t, s_c), compression damage factor (d_c), and tensile damage factor (d_t), as detailed in equation (16).

The direction factors of material stress state s_t and s_c are determined according to equations (17)–(18), where w_t and w_c are the stiffness recovery factors that control tension and compression, respectively. When defining the plastic damage parameters of concrete in the paper, $w_t = 0$ and $w_c = 1$ are taken, that is, assuming that when the concrete changes from compression to tension during the loading process, the previous degradation of tensile stiffness caused by tensile cracking cannot be restored. When the concrete is unloaded under tension and then loaded in reverse, the compressive stiffness of the concrete is completely restored.

$$E = (1-d)E_0 \tag{15}$$

$$(1-d) = (1-s_t d_c) E_0 (1-s_c d_t) \tag{16}$$

$$\begin{cases} s_t = 1 - w_t r^*(\sigma_{11}) \\ s_c = 1 - w_c\left(1 - r^*(\sigma_{11})\right) \end{cases} \tag{17}$$

$$r^* = H(\sigma_{11}) = \begin{cases} 1 & \sigma_{11} \geq 0 \\ 0 & \sigma_{11} \leq 0 \end{cases} \tag{18}$$

2.3.1.4 Calculation method for stress-strain relationship of concrete

The stress and strain values of concrete under uniaxial tension and compression are obtained according to the relevant formula of concrete uniaxial stress-strain curve given in Sections C.2.3 and C.2.4 of Appendix C of the Code for Design of Concrete Structures. Substitute the measured concrete material performance data into the relevant formulas in C-2.3 and C-2.4 for calculation, and then obtain the nominal stress and strain of the concrete material. Due to the provision in ABAQUS that the stress-strain relationship of concrete materials is defined by inputting the true stress and true strain, the nominal stress and strain are converted according to equations (19) and (20) before calculation, and then substituted into equations (19)–(20) for calculation:

$$\sigma = \sigma_{nom}\left(1+\varepsilon_{nom}\right) \tag{19}$$

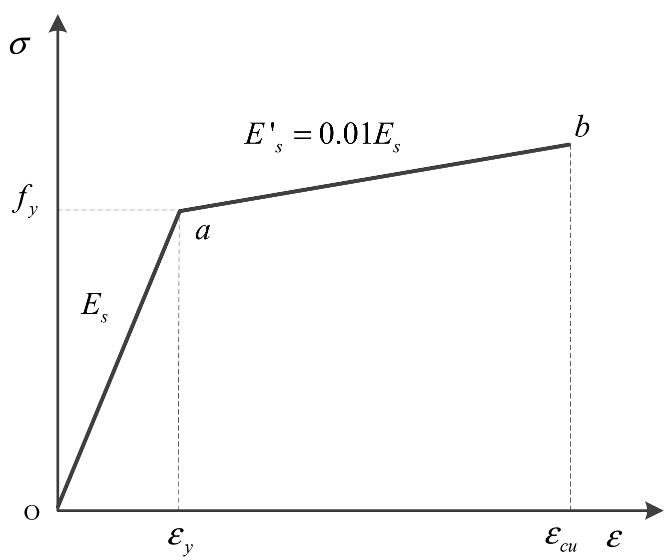
$$\varepsilon = \ln\left(1+\varepsilon_{nom}\right) \tag{20}$$

In the formula: σ_{nom}, ε_{nom} represents the nominal stress and strain of the material; σ, ε represents the true stress and strain of the material.

2.3.2 Constitutive model of steel and reinforcement

In finite element analysis, elastic-plastic models or dynamic strengthening models are commonly used to simulate the mechanical properties of steel under reciprocating loads. In the follow-up strengthening model, the double line follow-up strengthening model consists of the elastic stage before steel yield and the plastic stage after yield. It can describe the stress-strain relationship between steel and steel bars under reciprocating loads and greatly improve computational efficiency. Therefore, the double line follow-up strengthening model is used for both steel and steel bars in the text. As shown in Figure 5, the slope of the elastic stage O_a of the double line follow-up strengthening model is the measured material elastic modulus. When the material stress exceeds the yield strength of f_y and enters the strengthening stage *ab*, the elastic modulus is taken as 0.01 E_s.

Figure 3 Stress-strain relationship curve



The mathematical expression of the constitutive model is as follows:

$$\sigma = \begin{cases} E_s \varepsilon & \left(0 \le \varepsilon \le \varepsilon_y\right) \\ f_y + 0.01 E_s \left(\varepsilon - \varepsilon_y\right)\left(\varepsilon - \varepsilon_y\right) \end{cases} \tag{21}$$

In the formula: σ, ε – stress and strain of steel (reinforcement); f_y – yield strength of steel (reinforcement); σ_y – yield strain of steel (reinforcement); E_s – is the elastic modulus of steel (reinforcement).

2.4 Calculation of ultimate bearing capacity of reinforced concrete beams

Based on the constitutive model constructed in the previous section, the analysis of the mechanical performance of reinforced concrete beams is carried out, and the specific influence rules of each parameter on the ultimate bearing capacity of reinforced concrete beams are analysed. The univariate method formula fitting of the bearing capacity of reinforced concrete beams is carried out, and the relationship between the bearing capacity of reinforced concrete beams and the five parameters is known. It can be seen that when each parameter changes from small to large, the axial compression ratio is u, the longitudinal reinforcement ratio of beams is ρ, and the concrete strength is f_{cu}. The bending bearing capacity corresponding to a stiffness ratio of k_i between beams and columns increases, while the bearing capacity corresponding to a service life of t tons decreases. There is a linear relationship between M and u, k_i, and a quadratic correlation between ρ, f_{cu}, and t. Regression fitting was performed to obtain formulas (1)~(5), and the R^2 values of each fitting formula were greater than 0.98.

1 The relationship between bending bearing capacity and axial compression ratio u.

$$M_1 = 8.387u + 34.559 \tag{22}$$

2 The relationship between flexural bearing capacity and longitudinal reinforcement ratio of ρ.

$$M_2 = -9.340\rho^2 + 45.972\rho + 5.496 \tag{23}$$

3 The relationship between flexural bearing capacity and concrete strength f_{cu}.

$$M_3 = -0.00054 f_{cu}^2 + 0.5447 f_{cu} + 24.6877 \tag{24}$$

4 The relationship between flexural bearing capacity and the linear stiffness ratio of beams to columns k_i.

$$M_4 = 28.343k_i + 19.202 \tag{25}$$

5 The relationship between the bending bearing capacity and the service life of existing buildings of t tons.

$$M_5 = -0.0032t^2 + 0.0256t + 35.83 \tag{26}$$

Since the influence degree and specific rules of each parameter on the bending bearing capacity of the joint are quite different, and there is an unspecified interaction effect between the parameters, the multivariate mathematical model of the undetermined coefficient is established based on the regression equation fitted by the above five single parameters, as shown below:

$$M = a_3\left(u + b_2\right)\left(\rho^2 + c_2\rho + d_2\right)\left(f_{cu}^2 + e_2 f_{cu} + g_2\right)\left(t^2 + i_2 t + j_2\right) + l_2 \tag{27}$$

In the equation, all a_2, b_2, c_2, d_2, e_2, g_2, h_2, i_2, j_2, l_2 represent the values of the coefficients to be solved. Using origin software for multiple regression fitting, ten unknown coefficients were obtained as follows:

$$\left.\begin{aligned} a_2 &= -2.315\times10^{-8} \\ b_2 &= 4.121 \\ c_2 &= -4.922 \\ d_2 &= -0.5884 \\ e_2 &= -100.87 \\ g_2 &= -4571.66 \\ h_2 &= 0.67748 \\ i_2 &= -7.8125 \\ j_2 &= -11196.8 \\ l_2 &= 0.1745 \end{aligned}\right\} \tag{28}$$

Substitute each data into formula (28), and after integration, the formula for calculating the bending bearing capacity of multi-parameter nodes is as follows:

$$\begin{aligned} M &= 0.00134(u + 4.121)\left(-\rho^2 + 4.922\rho + 0.5884\right) \\ &(-0.0054 f_{cu}^2 + 0.5447 f_{cu} + 24.6877)\left(k_i + 0.67748\right) \\ &\left(-0.0032t^2 + 0.0256t + 35.83\right) + 0.07407 \end{aligned} \tag{29}$$

The recommended range of use for this formula is: axial compression ratio between 0.16 and 0.32, longitudinal reinforcement ratio between 0.79% and 1.40%, concrete strength, beam column linear stiffness ratio should not be greater than 0.570, and the ultimate bearing capacity of reinforced concrete beams with a service life of less than 32 years should be calculated. At this point, the main stress result obtained is the calculation result of the ultimate bearing capacity of reinforced concrete beams. This article analyses the mechanical properties of reinforced concrete materials, determines the strength parameters of concrete and steel bars, uses tensile tests to determine the tensile strength and shear yield limit of reinforced concrete beams, and uses the unified strength theory to analyse the main stress of reinforced concrete beams. Using the CDP model to simulate the mechanical properties of reinforced concrete components under reciprocating loads, based on the assumption of the unified strength theory, concrete and steel bars are considered as equivalent materials. The shear deformation method is used to calculate the ultimate bearing capacity of reinforced concrete beams, achieving the calculation of the ultimate bearing capacity of reinforced concrete beams based on the unified strength theory.

3 Experiment

3.1 Test loading device and measuring device

The experiment in this article was carried out in the testing hall of the Civil Engineering Large Structure Experimental Research Platform of M University. As shown in the figure, two L-shaped reinforced concrete piers are installed. Equipped with this L-shaped pier, on the one hand, it can reduce the lateral force generated when the opening beam is loaded with a large deflection. The L-shaped pier can provide effective torque cancellation, and on the other hand, it allows the pier to have a larger contact surface with the ground, providing heavier mass and increasing the friction between the pier and the ground. This can prevent the vibration of the opening beam during fatigue loading from causing the pier to shift, ensure the stability of the boundary conditions of the beam with openings. All the support points have been selected with high hardness round steel bars, which can provide a certain angle of rotation. The steel bars at the support pier are connected to the concrete support pier as a whole, and the rolling direction of the support steel bars is limited by the other two small steel bars. There is also a 25 mm thick steel plate as a backing plate between the steel rod and the concrete beam, which has sufficient rigidity to transmit force and can expand the contact surface between the support point and the beam to prevent local pressure from causing test failure. Considering the vibration displacement caused by fatigue load, it is necessary to limit the position of the concrete beam, otherwise unnecessary test accidents may occur. Therefore, all steel pads are welded with U-shaped channel steel to limit the lateral movement of the perforated beam. Similarly, the ends of the distribution beam and actuator are also limited as shown in the diagram, and all limits only constrain the lateral movement of the beam. The static loading of the test and the loading of the fatigue test are both completed by MTS high-frequency electro-hydraulic servo actuators.

Figure 4 Dynamic acquisition instrument (see online version for colours)

The acquisition system is the DH5921 dynamic stress and strain test and analysis system provided by Jiangsu Donghua Testing Technology Co., Ltd. It is a large and small multi-channel data acquisition system with 64 acquisition channels, which can be simultaneously connected to MTS sensors, Strain gauge and displacement meters, and can realise the measurement of force, displacement, voltage, temperature, etc. All measuring points are sampled synchronously, and the sampling frequency can reach 5 kHz. It is widely used in buildings, bridges mechanical and other static and fatigue tests.

Before the test, both sides of the test beam should be whitewashed. After drying, apply 50 mm ink on both sides of the beam with an ink hopper × A 50 mm grid is shown in Figure 5 to facilitate observation and recording of the location, width, and height of cracks. Because the load level imposed by the test is large, the concrete strain gauge is destroyed in the static stage, so the concrete strain gauge is not pasted on the beam surface. Finally, place the specimen on the support pier for levelling. This test is divided into static load test and fatigue test.

Figure 5 Beam surface treatment, (a) whitening treatment of beam surface (b) drawing grid of beam surface

(a) (b)

Fatigue load is controlled by load:

1 Perform pre loading 2–3 times, with the load ratio controlled within 60% of the cracking load, in order to check whether the equipment and collection instrument can work properly and eliminate the contact gap between the support and the beam.

2 After clearing all equipment to zero, load them in five levels according to the load level. After each level is completed, hold the load for 5–10 minutes, record the data collected by the collection instrument, and then complete crack observation, record the development of cracks, and take photos.

3 After reaching the upper limit of the load level, the unloading is still carried out according to five levels. After each level is completed, the load is held for 5–10 minutes, and only the data on the collection instrument is recorded during this stage.

4 After unloading, pre load 2–3 times again, and then adjust the MTS testing machine to fatigue mode for fatigue loading. The loading frequency of the fatigue test is 6 Hz.

After the fatigue cycle is loaded to 100,00, 50,000, and 80,000 times, stop and conduct a static test in steps 1–3. After the 80,000 cycles of fatigue are completed, perform a static ultimate load test on the specimen. After loading to the fifth level load, control the displacement at a rate of 0.2 mm/min. Carefully observe the changes in the beam during the process. To protect the loading device and measuring device, the static test ends when the specimen reaches 85% of the ultimate bearing capacity. If the fatigue cyclic loading process exhibits fatigue failure characteristics, it can be stopped and the static limit loading test can be conducted directly. If fatigue failure still does not occur after 80,000 cycles of fatigue loading, it indicates that the beam with openings within 80,000 cycles will not experience fatigue failure at this load level. The frequencies of the static and fatigue test collection instruments are 1 Hz and 50 Hz, respectively.

3.2 Experimental result

The calculation method proposed in this article was applied to calculate the ultimate bearing capacity of 20 reinforced concrete beams, and the results were compared with experimental results, as shown in Table 4 and Figure 6. The average ratio of the calculated value to the experimental value is 0.97, and the coefficient of variation is 0.073, indicating a good agreement between the calculated value and the experimental value.

Table 4 Comparison between calculated and experimental values of bearing capacity

Test piece number	N_{pre}/kN	N_{exp}/kN	N_{pre}/N_{exp}
S1	8 382	8 241	1.02
s2	9 072	9 632	0.94
s3	10 634	12 200	0.87
s4	8 561	8 767	0.98
s5	9 218	9 702	0.95
s6	8 492	8 261	1.03
s7	8 253	7 240	1.14
s8	8 552	9 650	0.89
s9	8 113	8 071	1.01

Note: N_{pre} is the calculated bearing capacity of steel tube concrete; N_{exp} is the bearing capacity of steel tube concrete test.

From Table 4 and Figure 6, it can be found that the proposed method for calculating the axial compressive bearing capacity of steel tube concrete shear walls based on the unified strength theory of double shear can accurately calculate the axial compressive bearing capacity of steel tube concrete shear walls.

Based on the above analysis, the accuracy analysis of the ultimate bearing capacity calculation of reinforced concrete beams will be carried out, and the accuracy of the ultimate bearing capacity calculation of reinforced concrete beams under the methods of Yu et al. (2021) and Tuo et al. (2022) will be statistically analysed. The results are shown in Table 5.

According to Table 5, when the number of iterations is 1,000, the accuracy of the calculation of the ultimate bearing capacity of reinforced concrete beams using Yu et al. (2021) method is 67.6%, the accuracy of the calculation of the ultimate bearing capacity of reinforced concrete beams using Tuo et al. (2022) method is 70.3%, and the accuracy of the calculation of the ultimate bearing capacity of reinforced concrete beams using this method is 93.5%. When the number of iterations is 5,000, the accuracy of the calculation of the ultimate bearing capacity of reinforced concrete beams using Yu et al. (2021) method is 78.2%, the accuracy of the calculation of the ultimate bearing capacity of reinforced concrete beams using Tuo et al. (2022) method is 79.5%, and the accuracy of the calculation of the ultimate bearing capacity of reinforced concrete beams using this method is 98.6%. The above results indicate that the prediction accuracy of this method is relatively high. This is because this article uses the CDP model to simulate the mechanical properties of reinforced concrete components under reciprocating loads. Based on the assumption of the unified strength theory, concrete and steel bars are regarded as equivalent materials, and the shear deformation method is used to calculate the ultimate bearing capacity of reinforced concrete beams. By analysing the deformation of concrete, the ultimate bearing capacity of reinforced concrete beams is calculated, effectively improving the accuracy of the bearing capacity calculation results.

Figure 6 Comparison between calculated bearing capacity and experimental bearing capacity

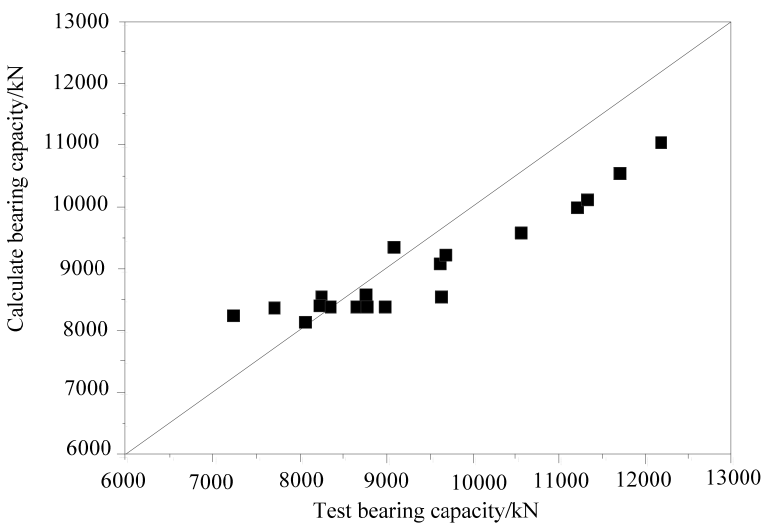


Table 5 Calculation accuracy of ultimate bearing capacity of reinforced concrete beams

Iterations/time	*Calculation accuracy of ultimate bearing capacity of reinforced concrete beams/%*		
	Yu et al. (2021) method	*Tuo et al. (2022) method*	*Proposed method*
1,000	67.6	70.3	93.5
2,000	69.3	75.7	98.6
3,000	70.8	78.1	99.2
4,000	72.3	69.2	96.0
5,000	78.2	79.5	98.6

4 Conclusions

The paper proposes a calculation method for the ultimate bearing capacity of reinforced concrete beams based on the unified strength theory. Analyse the mechanical properties of reinforced concrete materials, determine the strength parameters of concrete and steel bars, use tensile tests to determine the tensile strength and shear yield limit of reinforced concrete beams, analyse the main stress of reinforced concrete beams, use CDP models to simulate the mechanical properties of reinforced concrete components under reciprocating loads, and consider concrete and steel bars as equivalent materials based on the assumption of unified strength theory. Calculate the ultimate bearing capacity of reinforced concrete beams using the shear deformation method. The experimental results show that the accuracy of the ultimate bearing capacity calculation of reinforced concrete beams using this method can reach up to 99.2%, and the calculated values are in good agreement with the experimental values, indicating that this method can effectively improve the accuracy of the ultimate bearing capacity calculation of reinforced concrete beams.

In order to further improve the effectiveness of the calculation method for the ultimate bearing capacity of reinforced concrete beams, the influence of nonlinear behaviour of beams under large deformation on the ultimate bearing capacity will be considered in the future. Future research can delve deeper into the essence of these nonlinear behaviours and develop accurate and effective simulation methods suitable for practical engineering calculations.

References

Liu, J. (2021) 'A modified steel bar constitutive model considering the relative slip between steel bars and concrete', *Journal of Building Structures*, Vol. 42, No. S1, pp.448–455.

Peng, X., Hu, Y., Yang, T. and Wu, L. (2022) 'Analysis of shear resistance and ultimate bearing capacity of prefabricated monolithic prestressed concrete beams', *Hongshui River*, Vol. 41, No. 3, pp.128–133.

Tuo, C., Yu, Y., Chen, W., Guo, X., Wang, Z. and Xu, J. (2022) 'Prediction model of shear bearing capacity of reinforced recycled concrete beams based on Bayesian theory', *Journal of Xi'an University of Architecture and Technology (Natural Science Edition)*, Vol. 54, No. 2, pp.242–250.

Wu, F. and Zhong, M. (2022) 'Experimental study on the bearing capacity of reinforced concrete beams under overload', *Transportation Construction and Management*, Vol. 18, No. 2, pp.96–99.

Yan, Z. (2022) 'Finite element analysis of shear bearing capacity of reinforced concrete beams based on pressure path method', *Fujian Architecture*, Vol. 18, No. 3, pp.56–58+67.

Yu, B., Tao, X. and Ding, P. (2021) 'Uncertain analysis of calculation mode for shear bearing capacity of reinforced concrete beams', *Building Structure*, Vol. 51, No. 11, pp.82–87.

Zhang, Z. and Yang, M. (2021) 'Research on flexural fatigue performance of reinforced concrete beams strengthened with externally bonded FRP based on ABAQUS', *Journal of Nanjing University of Science and Technology*, Vol. 45, No. 1, pp.116–126.