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Research paper

Research on the design method of flexural capacity of RC beams strengthen by ultra-high-performance concrete

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Abstract: Due to the increase in traffic volume, load level, and service life of existing bridges, the bending bearing capacity of reinforced concrete beams (hereinafter referred to as RC beams) has decreased, leading to safety issues. In order to solve the problem of insufficient flexural bearing capacity of RC beams, this article adopts the method of ultra-high performance concrete (UHPC) flexural strengthening RC beams, establishes a finite element model of UHPC-RC reinforcement system, and conducts stress analysis with reinforcement thickness, reinforcement range, reinforcement form, and reinforcement height as parameters to determine the optimal scheme of the reinforcement system. Based on the calculation results, a theoretical formula for the maximum principal stress and maximum deflection of the reinforcement system is proposed. To verify the feasibility of the plan, a reinforcement design was carried out on an existing beam, and it was found that the bending bearing capacity of the RC beam increased by 21%; the high tensile strength of UHPC and the addition of steel fibers have a good limiting effect on cracks; The steel plate of the reinforcement system can be used as a template, reducing construction costs and having good economy.

Keywords: UHPC, RC beam bending reinforcement, bending bearing capacity, parameter analysis

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1. Introduction

Ultra-high performance concrete has higher compressive strength compared to ordinary concrete, and many scholars have applied it to structural reinforcement. In 2017, Liu Chao et al. [1] pointed out that ultra-high performance concrete can be applied to channel beam bridges. In addition, both theory and experiments have shown that UHPC thin layer reinforcement can effectively improve the stress state of the bridge deck, increase the stiffness of the bridge deck, and reduce the deformation of the bridge deck. In 2020, Xu Xiuying et al. [2] pointed out that ultra-high performance fiber reinforced concrete can be used for highway bridge reinforcement, which can increase the bridge deck's resistance to beam end deformation and reduce stress concentration. Then in 2021, Gao Qing et al. [3] conducted finite element simulation using ANSYS software to conduct experimental research on two channel beam bridges. It was turned out that on the two main beams reinforced with ultra-high performance concrete thin layers, the connection strength between the steel plate and the bridge significantly improved, the stiffness of the steel plate improved too, while the lateral stress of the steel plate effectively reduced, and the deflection of the steel plate was reduced as well.

At present, the commonly used methods for bridge reinforcement include the following. First, increasing the cross-section method, which involves pouring reinforcement on the outside of the original RC beam to provide it with a certain thickness of reinforced concrete thickening layer, thereby improving the bearing capacity of the original components [4]; second, the bonding reinforcement method, which uses steel plates or fiber composite materials to stick to the bottom of the beam [5, 6], and uses structural adhesive or anchor bolts to stick the steel plates or fiber composite materials to the bending surface or other weak parts of the reinforced concrete structure so as to improve the bearing capacity and durability of the reinforced concrete structure; third, prestressing reinforcement. This includes external prestressing reinforcement [7] and prestressing steel wire rope with polymer mortar surface layer reinforcement [8]; fourth, the transformation structural system reinforcement method, which adopts technical means to transform the stress system of the RC structure, redistributing the internal force of the original structure and reducing the internal force of the control section [9].

The main method for strengthening RC beams with UHPC bending is to increase the cross-sectional area, but there are differences. For example, the traditional method of in-creasing the cross-sectional area is to reinforce the bottom of the beam through the length and configure steel bars; however, in spite of the reinforcement method used in the text is also to add a layer of ultra-high performance concrete material to the beam body, the reinforcement plan in this article does not use full length reinforcement or steel bars, in-stead, it uses steel plates and bolts to achieve the reinforcement effect. On the one hand, ultra-high performance concrete has good bonding properties with existing bridges, and steel plates are used as templates for UHPC on the outer side of the reinforcement mate-rial; on the other hand, the steel plates are fixed to the beam body with bolts, where new and old materials can bear the force together.

2. Research method

2.1. Model design

This research is based on the reinforcement method of increasing the cross-section. To give an illustration, at the mid span position of the RC beam, a layer of ultra-high performance concrete is sprayed on the bottom section and sides of the beam. By controlling the thickness, reinforcement length, reinforcement surface, material performance, etc. of the sprayed ultra-high performance concrete, the internal force and deformation of the strengthened beam are compared. The mechanical analysis of the UHPC-RC reinforcement system was carried out using finite element analysis method, and the scheme design is shown in Fig. 1.

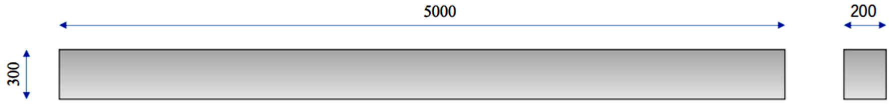

Fig. 1. Dimensions of the Original Beam (Unit: mm)

The original beam size is designed as: 5000 × 200 × 300 mm, with the structural cracking load (concentrated force) as the external load, which is applied at the mid span position of the main beam. The research will cope with the following issues:

1. Comparing the effectiveness of UHPC and ordinary concrete reinforcement beams under the same reinforcement thickness and length;
2. Testing the effect of different material reinforcement thicknesses on the main beam under the same reinforcement length;
3. Based on the determined optimal thickness, changing the reinforcement length to determine the optimal reinforcement length;
4. Comparing the advantages and disadvantages of three different reinforcement schemes based on the determined optimal reinforcement thickness and length. The three reinforcement schemes are: reinforcement only on the bottom surface, reinforcement only on two sides, and reinforcement on both sides as well as the bottom surface.
5. Finalizing the optimal reinforcement plan.

2.2. Material selection

The RC beam adopts C30 ordinary concrete, and the ultra-high performance concrete adopts C150 grade [10, 11]. The material parameters are shown in Table 1.

Table 1. Material Parameter Values

Material	Elastic modulus (MPa)	Poisson's ratio	Bulk modulus (Pa)	Shear modulus (Pa)	Density (kN/m^3)
Concrete	30000	0.18	1.56E+10	1.27E+10	2300
UHPC	60000	0.20	3.33E+10	2.50E+10	2500

2.3. Ansys model establishment

Using the static analysis module, establish an independent system and sketch a section of 200 × 300 mm in the XY plane. A beam with a length of 5000 mm is extruded, and reinforcement materials are installed at the bottom of the beam to consolidate with the original beam. Set the material properties, i.e., the main body of the beam is made of ordinary concrete, and the reinforcement part is made of ultra-high performance concrete), divide the grid (the grid is divided into quadrilaterals in units of 50 mm), apply loads on the top surface of the beam, add constraints, and make the beam in a simply supported state.

Establish several models with reinforcement thicknesses ranging from 10 mm to 50 mm. The reinforcement length ranges from 2 m to 4 m. The reinforcement materials are divided into two kinds: ultra-high performance concrete and ordinary concrete; their properties are compared so as to obtain the feasibility and applicability of ultra-high performance concrete bending reinforcement of RC beams. Then, using the above thick-ness range and extending the reinforcement length to establish multiple models to com-pare the results, finally, select the optimal reinforcement length. Spray ultra-high performance concrete of the same length and thickness as the bottom on both sides of the above model, and observe the reinforcement effect. Establish a partial model as shown in the following Fig. 2 to Fig. 3.

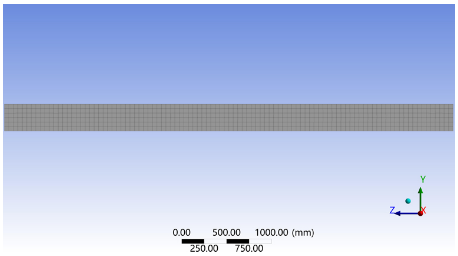

Fig. 2. RC Concrete Simply Supported Beam

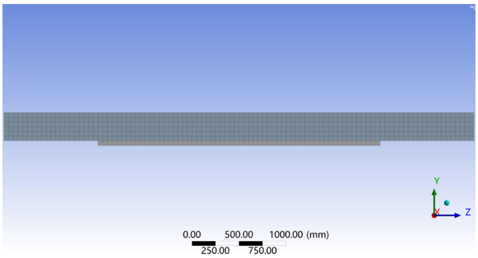

Fig. 3. UHPC-RC Reinforcement Model

2.4. Determination of applied load

Due to the lack of reinforcement, excessive force applied can lead to cracks and brittle failure in plain concrete beams. ANSYS software does not consider factors such as cracks and deflections that can reduce the load-bearing capacity of components when applying loads. In order to meet the actual situation, the cracking strength will be calculated based on the size of the beam to determine the magnitude of the applied force.

Given the design value of the tensile strength of C30 concrete being $f_t = 1.43$ MPa, the formula for the maximum bending normal stress is:

$$\sigma_{\max} = \frac{M}{I_z} y_{\max} \tag{2.1}$$

$$y_{\max} = 150 \text{ mm}, \quad \sigma_{\max} = 1.43 \text{ N/mm}^2$$

$$I_Z = \frac{bh^3}{12} = \frac{200 \times 300^3}{12} = 4.5 \times 10^8 \text{ mm}^4 \tag{2.2}$$

$$M = \frac{1.43 \times 4.5 \times 10^8}{150} = 4.29 \text{ kN} \cdot \text{m}$$

$$F = \frac{12M}{L} = \frac{4 \times 4.29}{5} = 3.432 \text{ kN}$$

3. Result and analysis

3.1. The influence of reinforcement materials on RC beams

In order to compare the effect of UHPC and ordinary concrete reinforcement materials on the bearing capacity of RC beams, ordinary concrete with the same reinforcement thickness was used as a reference. The calculation results are shown in Fig. 4–7.

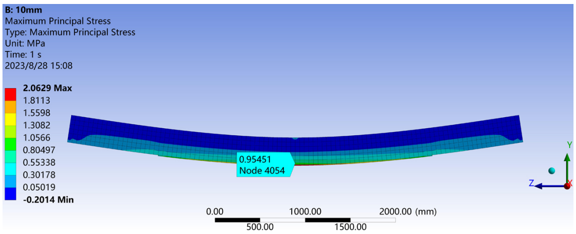

Fig. 4. Main Stress Diagram of 10 mm span reinforced with UHPC

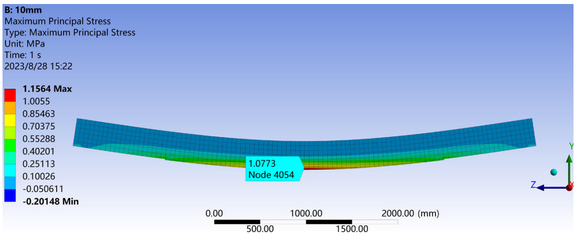

Fig. 5. Main stress diagram of 10 mm span reinforced with concrete

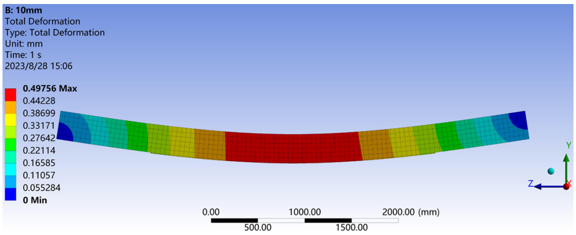

Fig. 6. Deflection Diagram of 10 mm reinforced with UHPC

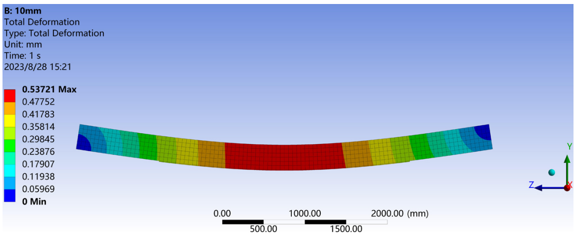

Fig. 7. Deflection Diagram of 10 mm reinforced with concrete

Under the same thickness conditions, the deflection and maximum main stress of RC beams reinforced with UHPC and C30 concrete materials are shown in Tables 2 and 3, Fig. 8. to Fig. 9.

Table 2. Deflection data for ordinary concrete and UHPC reinforcement within the range of different thickness (unit: mm)

Material	10 mm	15 mm	20 mm	25 mm	30 mm	35 mm	40 mm	45 mm	50 mm
UHPC	0.5	0.46	0.43	0.41	0.38	0.36	0.35	0.33	0.32
C30 concrete	0.54	0.51	0.49	0.47	0.45	0.44	0.42	0.4	0.39

Table 3. The maximum main stress of the beam body after reinforcement with ordinary concrete and UHPC within the range of reinforcement thickness (unit: MPa)

Reinforcement thickness	10 mm	15 mm	20 mm	25mm	30 mm	35 mm	40 mm	45 mm	50 mm
UHPC	0.95	0.85	0.76	0.68	0.62	0.56	0.51	0.46	0.42
C30 concrete	1.08	1.01	0.94	0.88	0.83	0.78	0.73	0.68	0.64

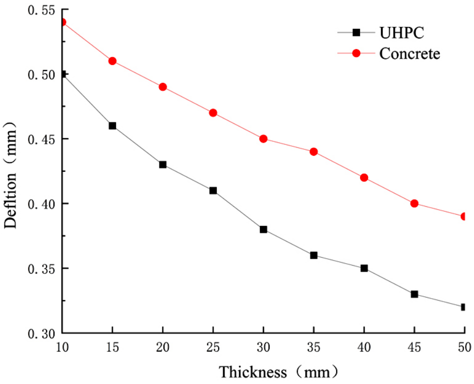

Fig. 8. Material thickness deflection curve

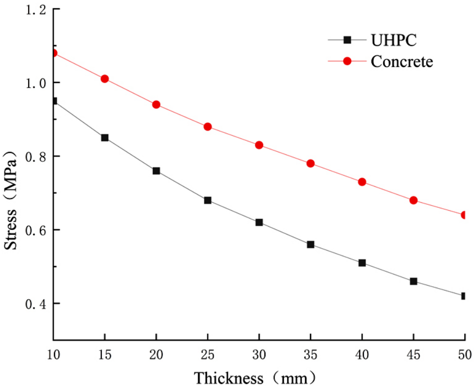

Fig. 9. Material thickness maximum main stress curve

According to Fig. 4 to 9 and Tables 2 to 3, the following conclusions can be drawn:

As to the impact on the stiffness of the main beam, it turns out that under the same thickness of UHPC and ordinary concrete materials used for reinforcement, the stiffness of the UHPC-RC reinforcement system increases more significantly. Under the same conditions, the increase in stiffness of the ordinary concrete reinforcement system ac-counts for approximately 66% that of the UHPC-RC reinforcement system.

When it comes to the impact on the strength of the main beam, it is concluded that under the same conditions, the strength of the UHPC-RC reinforcement system increases more significantly and that the strength improvement value of the ordinary concrete reinforcement system accounts for approximately 65% that of the UHPC-RC reinforcement system.

Based on the above analysis, it can be concluded that the strength and stiffness of the UHPC-RC reinforcement system are stronger than those of ordinary concrete reinforcement systems. Hence, UHPC is a good flexural reinforcement material.

3.2. The influence of reinforcement thickness on RC beams

From Fig. 8 and 9, it can be observed that the larger the reinforcement thickness, the smaller the mid span deflection and maximum principal stress of the reinforced beam. But when the thickness reaches a certain value, the decrease in main stress and mid span deflection tends to be gradual. This indicates that although the reinforcement effect will increase with the increase of reinforcement thickness, considering economic factors and the self-weight of the reinforcement material, the reinforcement material should not be too large. Otherwise it will not be fully utilized and would cause material waste. Besides, excessive thickness of the reinforcement material will lead to an increase in the self-weight of the reinforcement material and will increase the tensile stress between the original beam concrete and the UHPC section, consequently resulting in weak bonding between the reinforcement material and the beam body. It would even lead to the detachment of the reinforcement material under load.

According to the deflection curve, it can be seen that the slope of the curve decreases significantly when the reinforcement thickness is greater than 35 mm, and the stress curve also tends to flatten. When the reinforcement thickness is 35 mm, the deflection reduction value is 0.228 mm; with the reinforcement thickness reaching 50 mm, the deflection reduction value becomes 0.268 mm. The former is 30% less than the latter's self-weight, while the reinforcement effect is 85% of the latter. After comprehensive consideration, 35 mm reinforcement is determined as the optimal reinforcement thickness.

3.3. The influence of reinforcement length on RC beams

As the optimal thickness is set as 35 mm, the range of bottom reinforcement length (2–4 m) is changed. To determine the optimal reinforcement length, the analysis of de-flection and maximum principal stress data would be taken into consideration. The calculation results of stress and deflection are shown in Fig. 10–15. and Table 4, 5.

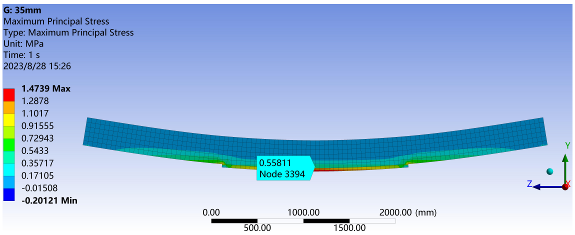

Fig. 10. Maximum main stress diagram for a reinforcement length of 2 m

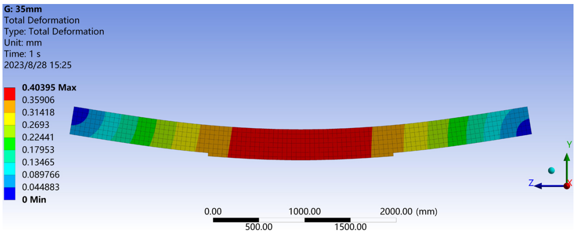

Fig. 11. Deflection diagram for a reinforcement length of 2 m

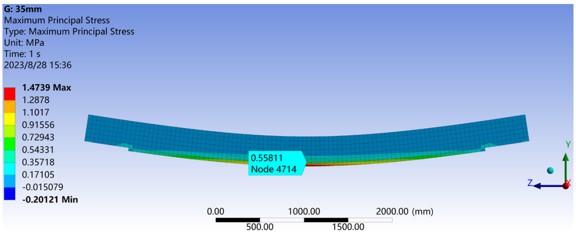

Fig. 12. Maximum main stress diagram for a reinforcement length of 4 m

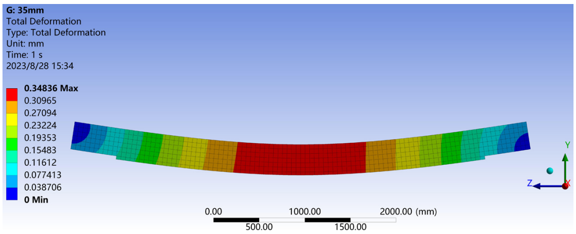

Fig. 13. Deflection diagram for a reinforcement length of 4 m

Table 4. Maximum main stress of the main beam within the reinforcement range

Reinforcement range	2 m	2.2 m	2.4 m	2.6 m	2.8 m	3 m	3.2 m	3.4 m	3.6 m	3.8 m	4 m
Maximum main stress (MPa)	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56

Table 5. Mid span deflection of main beam under different reinforcement conditions

Reinforcement range	2 m	2.2 m	2.4 m	2.6 m	2.8 m	3 m	3.2 m	3.4 m	3.6 m	3.8 m	4 m
Mid span deflection (mm)	0.404	0.393	0.384	0.376	0.370	0.364	0.359	0.355	0.352	0.35	0.348

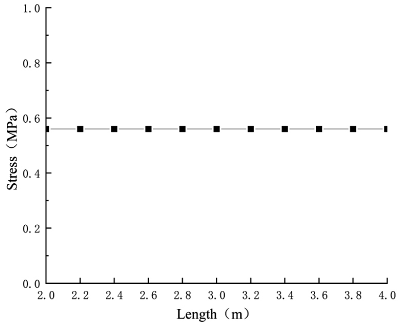

Fig. 14. Reinforcement Length- Maximum Main Stress Curve of the Main Beam

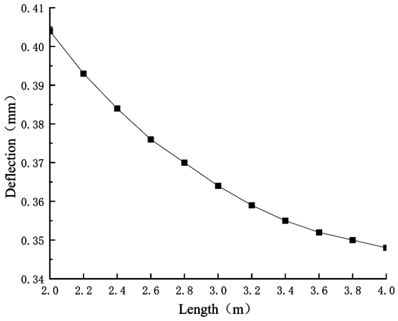

Fig. 15. Reinforcement length mid span deflection curve

From the maximum main stress of the beam body, it can be seen that under the same reinforcement thickness, different reinforcement lengths have almost no effect on the maximum main stress of the beam body. From the perspective of mid span deflection, the deflection of the beam strengthened by 4 m decreases by 0.240 mm, while the deflection of the beam strengthened by 3m decreases by 0.224 mm. The latter accounts for about 93% of the former; the difference in reinforcement effect is not significant. When the length is less than 3m, the reinforcement effect tends to increase significantly with the length; therefore, 3m is chosen as the optimal reinforcement range.

3.4. The impact of reinforcement schemes on RC beams

1. The model is shown in Figs. 16–18.

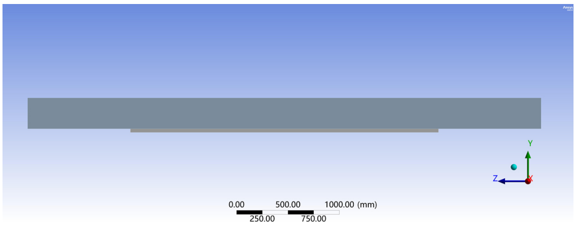

Fig. 16. Bottom reinforcement with a thickness of 35 mm

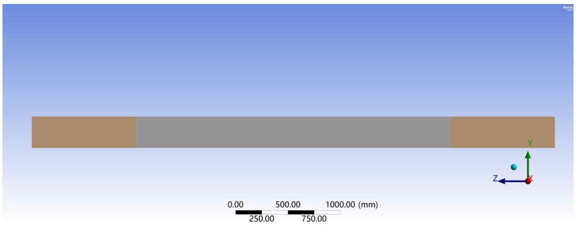

Fig. 17. Reinforcement on both sides with a thickness of 35 mm

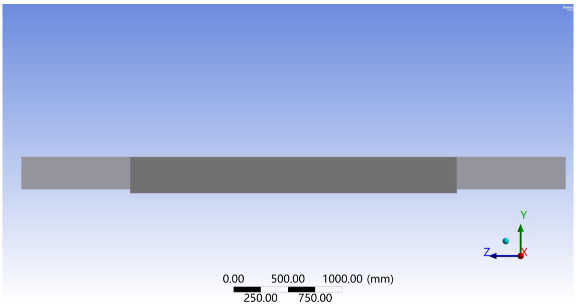

Fig. 18. Three sided reinforcement with a thickness of 35 mm

2. The analysis of the maximum main stress and deflection of three reinforcement methods under the same stress conditions ANSYS software establishes finite element models for three different reinforcement schemes. Calculation results are shown in Fig. 19, 20 and Table 6.

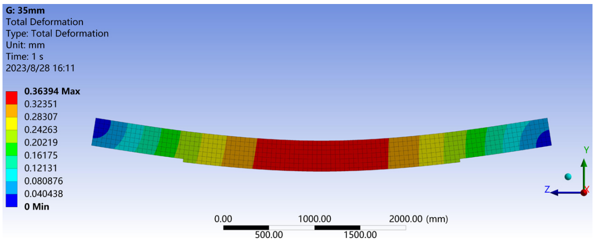

Fig. 19. Deflection of Bottom Reinforcement at 35 mm

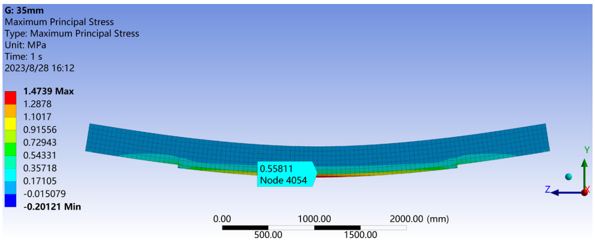

Fig. 20. Maximum main stress of 35 mm beam body with bottom reinforcement

Compared with the bottom reinforcement and the reinforcement on both sides, the difference in deflection between the two is not significant. From the perspective of the maximum main stress of the beam body, the bottom reinforcement method reduces the stress at the bottom of the beam by 0.675 MPa, while the two side reinforcement method reduces the stress at the bottom of the beam by 0.507 MPa. Thus, it can be concluded that the former has a better reinforcement effect by 33% more than the latter, and that the materials used for both side reinforcement are more than the bottom reinforcement. When considering economic factors, the bottom reinforcement method is also better than the two side reinforcement.

Table 6. Calculation results of three reinforcement schemes

	Reinforcement at the bottom	Reinforcement at both of the sides	Reinforcement from three sides
Deflection (mm)	0.364	0.366	0.248
Maximum main stress of beam body (MPa)	0.558	0.726	0.370

Compared with bottom reinforcement and three side reinforcement, in terms of deflection, three side reinforcement is significantly better than bottom reinforcement. The deflection of the latter reduces deflection by 0.34 mm, while the deflection of the former reduces by 0.224 mm. The beam deflection reduction value of three side reinforcement is 52% more than that of bottom reinforcement. From the maximum main stress of the beam body, the latter reduces by 0.863 MPa, which is 28% more than the former. In summary, the three-sided reinforcement method has a more significant effect on improving the strength and stiffness of RC beams.

3.5. The influence of reinforcement height on the side of the beam on RC beams

Selecting a height range of 50–300 mm for lateral reinforcement, with a difference of 25 mm, 11 heights were selected for parameter analysis. Part of the calculation results are shown in Figs. 21–26 and Table 7.

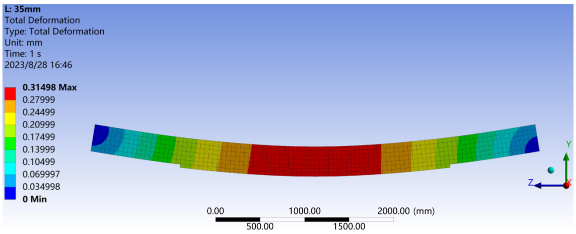

Fig. 21. Mid span deflection at a reinforcement height of 100 mm

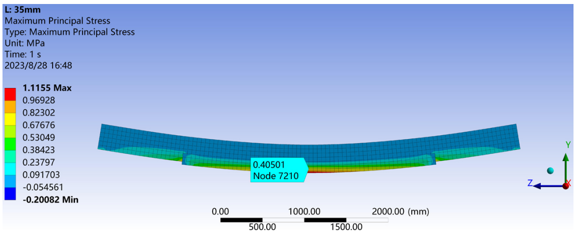

Fig. 22. The maximum main stress of the beam when the reinforcement height is 100 mm

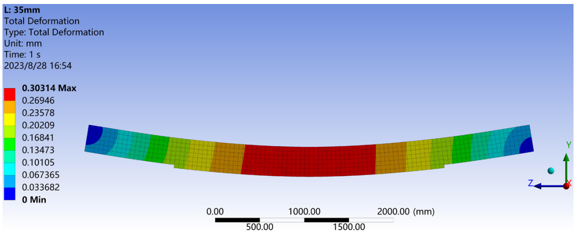

Fig. 23. Mid span deflection at a reinforcement height of 200 mm

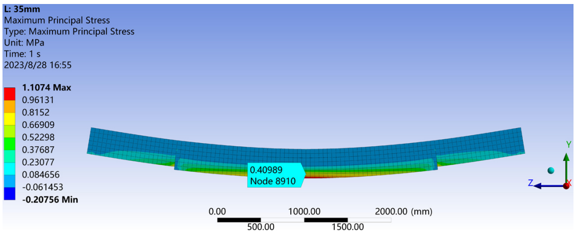

Fig. 24. The maximum main stress of the beam when the reinforcement height is 200 mm

Table 7. Finite Element Simulation Calculation Results for Different Reinforcement Heights

Height (mm)	50	75	100	125	150	175	200	225	250	275	300
Deflection (mm)	0.318	0.315	0.315	0.315	0.313	0.31	0.303	0.293	0.281	0.265	0.248
Main stress (MPa)	0.416	0.407	0.405	0.406	0.408	0.41	0.41	0.406	0.398	0.386	0.37

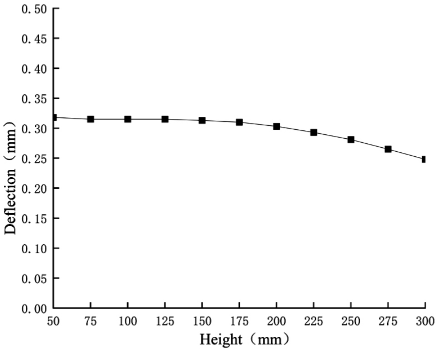

Fig. 25. Reinforcement height deflection curve

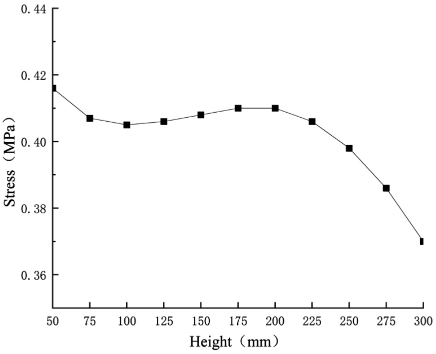

Fig. 26. Reinforcement height maximum main stress curve

From the perspective of deflection, the influence of different reinforcement heights on deflection is not significant. The reduction in deflection when reinforced at a height of 300 mm is 0.34 mm compared to that of the original beam. The reduction in height of reinforcement 50 mm is 0.27 mm, accounting for 80% that of the reinforcement 300 mm.

When looking at the maximum main stress of the beam body, it is reduced by 0.863 MPa when reinforced by 300 mm compared to that of the original beam. The decrease in height of reinforcement 50 mm is 0.817 MPa, accounting for 95% of the reinforcement 300 mm.

From the two aspects, the reinforcement height does not have a significant impact on the reinforcement effect. Considering the bonding between the reinforcement material and the beam body, as well as the subsequent required structural measures, the optimal height is approximately 100 mm.

3.6. Derivation of strength and stiffness calculation formulas for UHPC-RC reinforcement system

The range of beam reinforcement length has a significant impact on the deflection of RC beams. The following formula is derived for analysis based on considering both full beam reinforcement and changing the reinforcement length range.

3.6.1. Deflection and main stress of UHPC-RC reinforcement system under full beam re-inforcement conditions

1. Calculation of the moment of inertia according to reference [12]
   Taking reinforcement of 35 mm as an example:
   Convert the reinforced section as shown in Fig. 27.

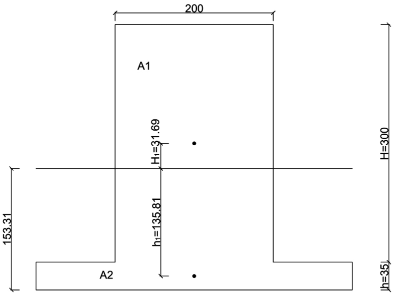

Fig. 27. Cross section after calculating moment of inertia conversion

Neutral axis position after reinforcement:

$$y = \frac{200 \times 300 \times (35 + 150) + 400 \times 35 \times 35/2}{200 \times 300 + 400 \times 35} = 153.31 \quad \text{mm}$$

Moment of inertia after reinforcement:

$$I = \frac{bH^3}{12} + A_1 H_1^2 + \frac{bh^3}{12} + A_2 h_1^2 \tag{3.1}$$

$$I = \frac{200 \times 300^3}{12} + 200 \times 300 \times 31.69^2 + \frac{400 \times 35^3}{12} + 400 \times 35 \times 135.81^2$$
$$= 76.99 \times 10^7 \quad \text{mm}^4$$

2. Maximum principal stress of beam body:

$$\sigma_{\max} = \frac{M}{I_z} y = \frac{3.75 \times 10^6 \times 118.31}{76.99 \times 10^7} = 0.576 \text{ MPa} \tag{3.2}$$

   The ANSYS calculation results account for approximately 97% of the manual calculation results.
3. Mid-span deflection
   The ANSYS calculation results account for approximately 97% of the manual calculation results. The elastic modulus used for calculating deflection is converted based on the volume of two materials:

$$\begin{aligned} E' &= \frac{E_1 \times A_1 + E_2 \times A_2}{A} \\ &= \frac{30000 \times 200 \times 300 + 60000 \times 200 \times 35}{200 \times 335} = 33134 \text{ MPa} \\ \omega &= \frac{3 \times 10^3 \times 5000^3}{48 \times 33134 \times 76.99 \times 10^7} = 0.31 \quad \text{mm} \end{aligned} \tag{3.3}$$

   The manual calculation results account for 86% of the software calculation results.

The theoretical calculation results of the reinforcement system under the thickness of reinforcement are shown in Table 8.

Table 8. Manual Calculation Result Data

Type	10 mm	15 mm	20 mm	25 mm	30 mm	35 mm	40 mm	45 mm	50 mm
Deflection (mm)	0.44	0.39	0.35	0.31	0.33	0.31	0.29	0.22	0.2
Stress (MPa)	0.974	0.87	0.78	0.7	0.635	0.576	0.524	0.48	0.44

Analysis of deflection results: Considering that there is not much difference in the percentage of deflection calculated by hand for different reinforcement thicknesses compared to the percentage calculated by computer, the average value of the percentage (excluding the maximum and minimum values) is taken as 81%.

Analysis of stress results: Considering that the software calculation of the maximum main stress of the beam body with different reinforcement thicknesses has little difference in the percentage of manual calculation, the average value of the percentage (excluding the maximum and minimum values) is taken as 97%.

3.6.2. The delfection and main stress of UHPC-RC when changing reinforcement conditions

1. According to the previous research results, if the maximum main stress of the beam remains unchanged when the reinforcement length is changed, it can be considered that the reinforcement thickness is the influencing factor for changing the maximum main

stress of the beam. However, there is always a gap between the theoretical results and the software calculation results, and a certain reduction coefficient should be taken into consideration. Taking 0.97 as the reduction factor for comprehensive consideration, the theoretical results are close to the actual results. The specific formula is as follows:

$$\sigma_{\max} = 0.97\frac{M}{I_z}y_{\max} \tag{3.4}$$

2. When the reinforcement thickness is 35 mm, changing the reinforcement length also changes the deflection. The ratio between the results of finite Metacomputing and theoretical calculation is shown in Fig. 28 and Table 9.

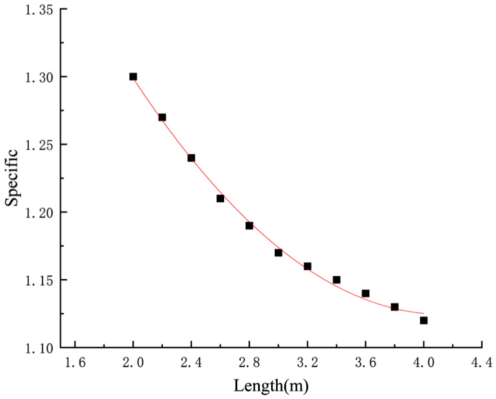

Fig. 28. Scatter plot and fitting curve of the ratio between software and manual calculation results

Table 9. Ratio of software calculation and manual calculation results for different reinforcement lengths

Reinforcement range	2 m	2.2 m	2.4 m	2.6 m	2.8 m	3 m	3.2 m	3.4 m	3.6 m	3.8 m	4 m
Mid span deflection (mm)	1.30	1.27	1.24	1.21	1.19	1.17	1.16	1.15	1.14	1.13	1.12

Use the software Origin to carry out regression analysis on the above data with a unitary quadratic function, take the reinforcement length as the function x, and the ratio of the two is y, hence obtaining the following:

$$y = 0.04x^2 - 0.33x + 1.8 \tag{3.5}$$

in the formula, x represents the reinforcement length.

It can be inferred that when the reinforcement length is between 2–3m, the following formula can be used in order to make the theoretical results similar to the actual results:

$$\omega = (0.0382x^2 - 0.32x + 1.8)\frac{Fl^3}{48EI} \tag{3.6}$$

4. Strengthening design of practical engineering

4.1. Project overview

The Bridge M was completed in 1997, with a carriageway width of 9.0 m, a total length of 165 m, a total width of 12.6 m on the bridge deck, and a span combination of 8 spans of 20 m.

The upper structure of the bridge is a simply supported T-beam with 7 pieces per span. The lower structure is a gravity abutment and the pier is double column cylindrical pier, and the pier foundation of the bridge is pile foundation; The bridge deck is paved with cement concrete pavement. The design load is level 20 for automobiles, and the bridge deck photo is shown in Fig. 29. According to the bridge inspection results, there are many transverse cracks in the middle of the main beam span, and the bridge's bending bearing capacity is insufficient, requiring reinforcement treatment.

Fig. 29. Bridge Elevation View

4.2. Calculation results and analysis of the original beam

4.2.1. Structural parameters and model establishment of the original beam

Midas Civil was used to establish a bridge model for calculation. In order to analyze the lateral effects of the structure, the model adopted the beam grid method to calculate the stress situation of the bridge before reinforcement. The load standard of the model is: Highway I; C30 concrete was adopted as the main body of the bridge, which is the main design parameters. The model is established using CAD import, first establishing the required sections and materials in Midas Civil. Then CAD drawing is used to create different layers for different components, making it easy to import. And when importing, different sections and materials are assigned according to different components. Since there is no connection between T beams, in order to consider the lateral effect of T-beam, the beam grid method is used for modeling: the bridge is horizontally arranged with a virtual beam with zero gravity and releasing the bending moment in y-direction. The model mainly considers the self-weight of the structure, guardrail load, bridge deck pavement, and vehicle load (two lanes). The beam end constraint is set to a simply supported beam. The discrete diagram of the model is shown in Fig. 30.

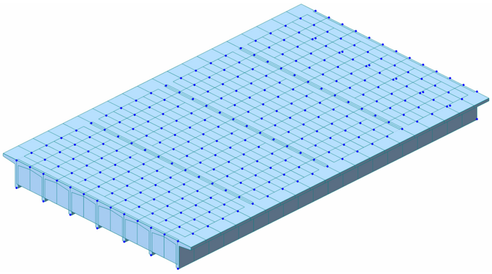

Fig. 30. Finite Element Model of T-beam

4.2.2. Load Combination

During the operation of the bridge, multiple loads occur simultaneously, and the combination coefficients under combined conditions are shown in Table 10. The calculation results are shown in Table 11 and Fig. 31.

Table 10. Load Combination

Combined working conditions	Self-weight	Guardrail load	Bridge deck pavement	Vehicle load
Basic Combination	1.2	1.2	1.2	1.4

Table 11. Calculation Results

Combined working conditions	Maximum mid span bending moment (kN·m)	Maximum support shear force (kN)
Basic Combination	2873.2	1033.0

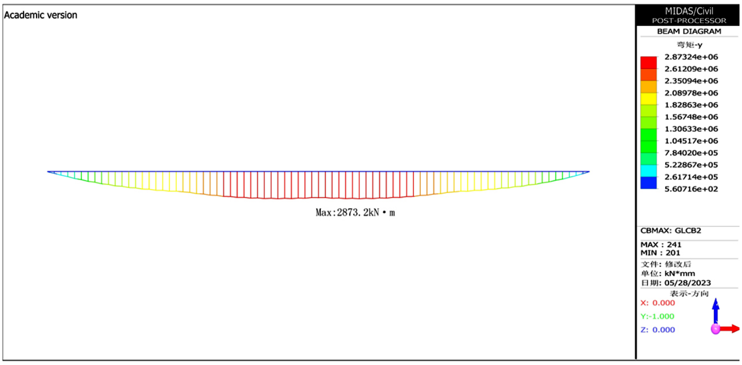

Fig. 31. Maximum bending moment diagram

4.2.3. Calculation of bending bearing capacity

As this design is for ultra-high performance concrete flexural reinforcement RC beams, it is necessary to verify the flexural bearing capacity of the T-beam. According to the reinforcement of the bridge, the longitudinal reinforcement of the T-beam is selected as HRB300 grade, adopting 8 steel bars with a diameter of 32 mm and 2 steel bars with a diameter of 20. The cross-sectional dimensions and reinforcement of the T-beam are shown in Fig. 32.

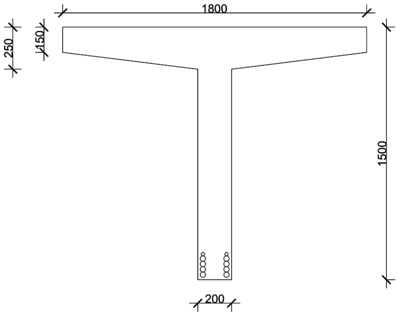

Fig. 32. Cross section of T-beam

Calculation of the flexural bearing capacity of the T-beam's normal section:

– The thickness of the concrete protective layer is 30 mm, the effective height 1394 mm. Determine the type of T-beam using the following formula:

$$f_y A_s = 270 \times 7062 = 1906.74 \text{ kN}$$

$$\alpha_1 f_c A = 1.0 \times 14.3 \times (1800 + 200) \times 250 \div 2 = 3575 \text{ kN}$$

$$f_y A_s < \alpha_1 f_c A$$

– Therefore, it belongs to the first type of cross-section.

To obtain the value of x:

Assuming $x < 150$ mm,

$$\alpha_1 f_c b'_f x = 1906.74 \text{ kN}$$

$$x = 74.1 \ \text{ mm} < 150 \ \text{ mm}$$

– To conclude, assumption is correct.

To obtain the bending capacity:

$$M = f_y A_s (h_0 - \frac{x}{2})$$

$$M = 270 \times 7062 \times \left(1394 - \frac{74}{2}\right) = 2587.45 \text{ kN} \cdot \text{m}$$

$$2587.45 \text{ kN} \cdot \text{m} < 2873.2 \text{ kN} \cdot \text{m}$$

The bending capacity of the T-beam before reinforcement is less than the maximum combined bending moment, indicating that the bending capacity of the bridge is insufficient.

4.3. Calculation results and analysis after bridge reinforcement

4.3.1. Bridge reinforcement plan

According to the research results in Chapter 3, a three-sided reinforcement scheme is adopted, with a reinforcement length of 3 m, a thickness of 35 mm, a height of 100 mm on both sides, and a reinforcement of 12 m. The reinforcement section is shown in Fig. 33.

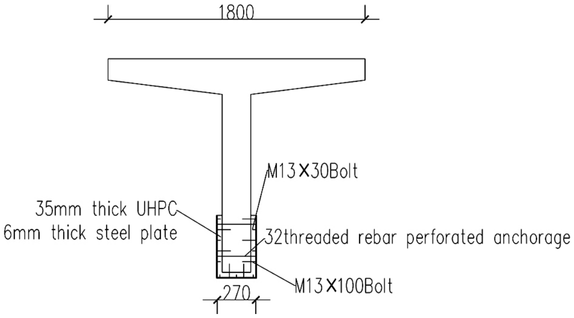

Fig. 33. Schematic diagram of T-beam reinforcement

Consider the self-weight of the reinforcement material and recalculate the internal force of the reinforced structure. The calculation results are shown in Fig. 34.

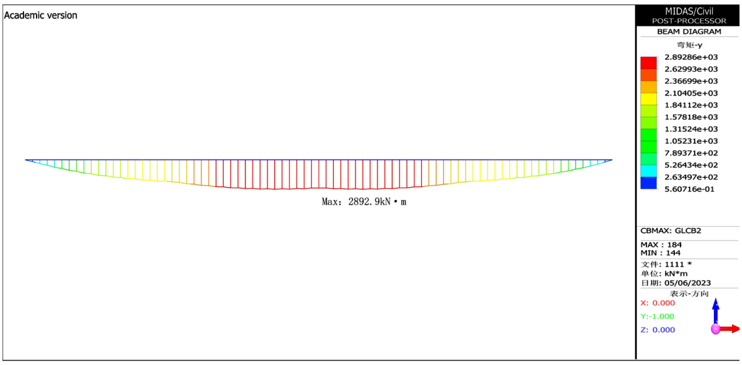

Fig. 34. Maximum bending moment diagram of T-beam after reinforcement

4.3.2. Calculation of the flexural bearing capacity of the reinforced normal section

The standard value of axial tensile strength of UHPC material is 7 MPa, and the design value of tensile strength is 5 MPa. In order to fix the UHPC material, a 6 mm thick steel plate (HRB335) is wrapped around the reinforcement material and fixed with bolts. Therefore, the bending effect of the steel plate should be considered. According to the previous research results, the flexural bearing capacity of the reinforced structure is as follows:

$$M = f_y A_s \left(h_0 - \frac{x}{2}\right) + f_{t1} A_1 \left(h_0 - \frac{x}{2} + \frac{t}{2}\right) + f_{y0} A_0 (h_0 - \frac{x}{2} + t + \frac{t_1}{2}) \tag{4.1}$$

In the formula, what the parameters refer to are listed as follows:
f_{t1} – UHPC tensile strength design value (MPa),
$A_1 A_0$ – reinforced bottom UHPC material, steel plate area (mm^2),
t, t_1 – UHPC material, steel plate thickness (mm),
f_{y0} – design value of tensile strength of steel plate (MPa),

$$M = 270 \times 7062 \times \left(1394 - \frac{74}{2}\right) + 5 \times 35 \times 200 \left(1394 - \frac{74}{2} + \frac{35}{2}\right)$$

$$+300 \times 6 \times 200 \times \left(1394 - \frac{74}{2} + 35 + \frac{6}{2}\right) = 3137.76\ \mathrm{kN \cdot m} > 2892.9\ \mathrm{kN \cdot m}$$

The flexural bearing capacity of the UHPC-RC reinforcement system is greater than the combined value of load effects, indicating that the strengthened bridge can meet safety requirements.

5. Conclusions

This article uses ANSYS software to establish multiple sets of finite element models for comparative calculation, and determines the optimal reinforcement plan. In order to verify the applicability and rationality of the reinforcement plan, the Midas Civil software is used to model the reinforcement design of an existing T-beam with insufficient bending bearing capacity, simulate the actual situation of the beam, calculate the internal force, and perform a series of verification calculations. The main conclusions were drawn as follows:

1. The basic conclusion drawn is that under the conditions of this article, the more reinforcement materials, the better the reinforcement effect would be. However, after exceeding a certain limit, the reinforcement effect is no longer significant. Therefore, considering the overall conditions of this article, the best reinforcement plan is listed as follows: UHPC material adopts three-sided reinforcement, reinforcement thickness reaches 35 mm, reinforcement length using 3000 mm, and side reinforcement height adopts 100 mm.
2. Based on the comparison between ANSYS software calculation results and manual calculation results, we have summarized a theoretical formula, which is to multiply the theoretical formula by a function (obtained by software fitting, serving as a coefficient), in order to make the theoretical settlement results closer to the actual results (ANSYS calculation results).
3. For the reinforcement of an actual bridge, UHPC material is used and wrapped with steel plates for fixation. The reinforcement is 12 m long, 35 mm thick, and 400 mm high on both sides. After reinforcement, the bearing capacity of the bridge will be significantly improved. According to the above calculation, the bearing capacity after reinforcement has increased by 21%. During the reinforcement process, as ultra-high performance concrete does not use coarse aggregate, it can fill the cracks that have already been generated in the original beam, which has a good limiting effect on the occurrence of cracks and can improve the stress state and reduce deflection. Besides, this reinforcement method is convenient for construction, and the reinforced steel plate can serve as a template to further control construction costs, which has good practicality.

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2. Research on Mechanical Characteristics and Design Method of hoop constraint UHPC Spherical Hinge in Bridge Swivel, Pre-research project of National Natural Science Foundation of Anhui Polytechnic University, and the project number is Xjky2022173.
3. Study on mechanical characteristics and design method of ultra-high performance concrete spherical hinge translational system under multi factor coupling, The Initial Scientific Research Funds of Anhui polytechnic University", and the project number is 2021YQQ021.

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