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Research paper

Parameter analysis and design method of ultra-high performance concrete shear strengthening RC beams

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Abstract: In recent years, bridge safety accidents caused by insufficient shear bearing capacity of bridges have attracted increasing attention. The main causes include internal factors such as insufficient bridge section and deterioration of steel bars, as well as external factors, for example, vehicle load surge and improper maintenance. To address this issue to some degree, this article adopts the method of strengthening RC beams with ultra-high performance concrete (UHPC) and conducts parameter analysis using finite element method, taking into consideration the influence of four parameters: reinforcement material, reinforcement thickness, reinforcement length, and reinforcement form on the shear strengthening characteristics of RC rectangular beams. After obtaining the optimal reinforcement plan through parameter analysis, the author applied the research results to an existing bridge with insufficient shear strength. It then turned out that the shear bearing capacity of the reinforced bridge's inclined section increased by approximately 27.1%. Simple and fast in construction, this reinforcement method is one of the methods that is effective to increase cross-section reinforcement; besides, it features good economic characteristics and applicability.

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

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1. Introduction

Based on the excellent mechanical properties, good durability, and cross-sectional bonding characteristics of UHPC, researchers have conducted extensive research on the reinforcement characteristics of UHPC. In recent years, many achievements have been made in the study of the bending performance of RC beams strengthened with UHPC [1–7], but there is[relatively insufficient research on the shear performance of the UHPC-RC system. The traditional UHPC shear reinforcement method usually uses UHPC as[the main load-bearing material to reinforce the section, and ordinary steel bars are added to the UHPC reinforcement layer to enhance the mechanical properties of the reinforcement layer so as to delay cracking.

In 2021, Songling H [8] proposed a new method of strengthening RC bridges with prestressed ultra-high performance concrete, aiming to provide more efficient and durable reinforcement and protection for degraded bridges. Through static bending tests on 8 beams, the failure morphology, cracking performance, flexural bearing capacity, and deformation characteristics of beams strengthened with different UHPC reinforcement parameters were studied. A theoretical calculation formula for the cracking strength and flexural bearing capacity of UHPC reinforced beams was proposed by considering the coupling effect of post cracking strain hardening, prestressing, and the restrained shrinkage effect of the reinforcement layer.

In 2022, Jiang H [9] used ABAQUS to conduct nonlinear analysis on rectangular reinforced concrete beams, simulating basalt fiber cement-based composite materials, and analyzing the shear strengthening effect of different concrete strength (C30, C35, C40) beams on B-FRCM reinforced RC beams. It turns out that the shear bearing capacity of RC beams strengthened with B-FRCM has significantly improved.

In terms of shear reinforcement of RC beams, there are mainly methods such as pasting steel plates, increasing cross-section, fiber reinforced composite material reinforcement, and external prestressing reinforcement. The method of increasing cross-section is a method that is easy to maintain and also featured with durable, and low-cost characteristics for shear strengthening RC beams, which can provide reliable guarantees for the safe use of structures. In this paper, the finite element model of RC beam is established based on the enlarged section method, and the mechanical analysis of the Shear stress of the strengthened UHPC-RC system is carried out through multiple parameters. The final application of the research results in practical engineering has good economic characteristics and applicability [10–13].

2. Research method

In order to further study the reinforcement of rectangular beams with ultra-high performance concrete, this article mainly uses Ansys software to establish a simple supported beam model with a section width of 200 mm, a height of 300 mm, and a span of 5000 mm. By analyzing the strength and stiffness of the structure, the optimal reinforcement material, thickness, length, and method are obtained.

2.1. Material parameters

The values of concrete parameters are shown in Table 1 [14, 15].

Table 1. Basic parameters of materials

Material	Density (kN/m^3)	Elastic modulus (MPa)	Poisson ratio	Bulk modulus (MPa)	Shear modulus (MPa)
Concrete	2300	30000	0.18	15600	12700
UHPC	2500	60000	0.20	33300	25000

2.2. Selection of model parameters

The finite element model adopts the solid element model in ANSYS software, and the dimensions and parameters of each part are as follows.

1. The concrete beam section size is 200 × 300 mm, and the calculated structural span is 5000 mm.
2. Select the left node of the beam, constrain the displacement in the X and Y directions, simulate the fixed hinge support. On the right node is roller support.
3. A vertical concentrated load is applied to the beam of the finite element model, which is less than the ultimate failure load of the concrete beam. The basic size of the mesh is 50 × 50 × 50 mm; and the solid unit is divided by hexahedron.
4. The model adopts the single-point loading method, applies a concentrated force of the cracking load at the midpoint of the beam, observes the maximum shear stress value of the center (point A, Fig. 3) of the beam section at 100 mm from both sides of the support, and selects the optimal reinforcement method.

The beam ultimate load calculation is as follows:

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

$$y_{\max} = 150 \text{ mm}$$

$$\sigma_{\max} = 1.43 \text{ kN/mm}^2$$

$$I_Z = \frac{bh^3}{12} = \frac{200 \times 300^2}{12} = 4.5 \times 10^8 \text{ mm}^4 \tag{2.2}$$

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

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

For the convenience of calculating,concentrated load is taken as 3 kN.

2.3. Establishment of finite element model

The finite element model is shear reinforced at the beam end position, and the reinforcement materials are compared and analyzed by UHPC and C30 concrete. By taking the reinforcement thickness, reinforcement length, reinforcement material and reinforcement method as parameters, the stress state of the main beam was compared. The mentioned reinforcement method then adopts three methods: bottom-double side reinforcement method, double side reinforcement method and single side reinforcement for comparative analysis. When it involves bottom-double side reinforcement, the reinforcement length is set to the reinforcement range of 1000 mm at the beam end, and the reinforcement method and reinforcement length are determined by the control variable method so as to gain the optimal scheme about reinforcement material and reinforcement thickness. RC beam and UHPC-RC Reinforcement System are shown in Fig. 1 and 2.

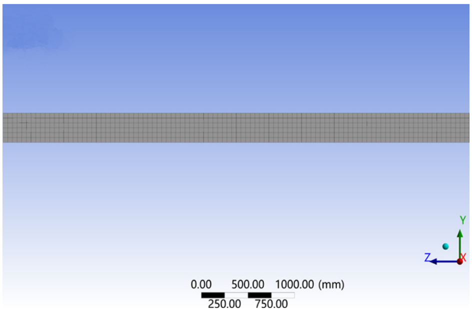

Fig. 1. Finite element model of RC beam

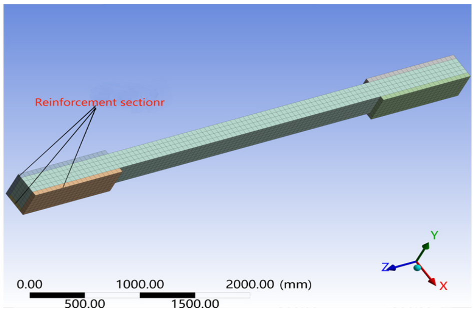

Fig. 2. Finite Element Model of UHPC-RC Reinforcement System

3. Results and analysis

3.1. Effect of reinforcement materials on RC beams

This paper compared the mechanical properties of the main beam when UHPC and C30 concrete were used as shear reinforcement materials, and the shear bearing capacity of UHPC-RC reinforcement system was determined by comparing the maximum shear stress values of different reinforcement materials. During the modeling analysis, the reinforcement range is within 1000 mm of the fulcrum on both sides. When the thickness of the two reinforcement materials is 10 mm, 25 mm and 50 mm, the shear stress values of RC beam at Point A (the center position) are shown in Fig. 3–5.

From the Table 2, it can be seen that at the center of the RC beam, the shear value of the beam reinforced with C30 concrete is greater than that of the UHPC reinforced beam. When the reinforcement thickness becomes 25 mm, the shear value after UHPC being reinforced only accounts for 81% of the reinforcement value of C30 concrete. Thus the shear resistance of UHPC is relatively better.

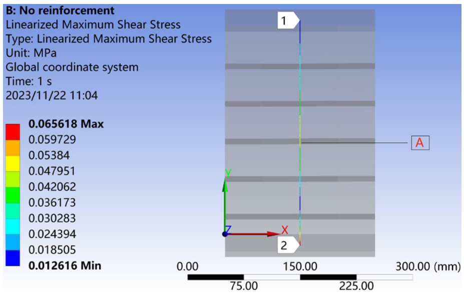

Fig. 3. The original beam not reinforced
the original beam

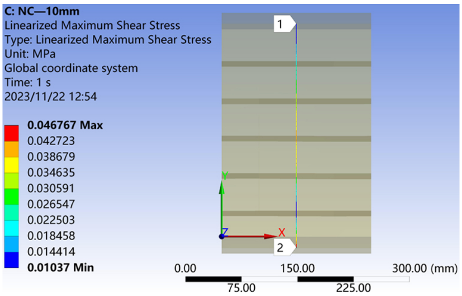

Fig. 4. RC reinforcement thickness at 10 mm

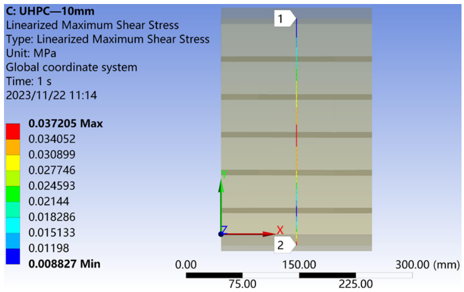

Fig. 5. UHPC reinforcement thickness at 10 mm

Table 2. Shear stress values at point A

Reinforcement thickness	10 mm (MPa)	25 mm (MPa)	50 mm (MPa)
C30 concrete	0.0378	0.0328	0.0251
UHPC	0.0353	0.0265	0.0188

3.2. Effect of reinforcement thickness on RC beam

The proposed reinforcement range of the model is 1000 mm for the fulcrum on both sides, and the reinforcement thickness is set from 10 mm to 50 mm according to the on-site construction quality of the reinforcement material. The thickness parameters were analyzed in ten groups taking 5 mm as the variable, and the maximum shear stress cloud at centroids position (point A) was compared and analyzed. The calculation results are shown in Table 3 and Fig. 7. Fig. 6 shows the maximum shear stress cloud of the concrete beam when the reinforcement thickness is 20 mm.

According to Fig. 7, The maximum shear stress of the center point in Fig. 7 curve increases significantly with the increase of reinforcement thickness. It dropped 0.0018 MPa when the thickness increases from 30 mm to 35 mm and 0.0013 MPa from 35 mm to 40 mm, accounting for only 72% of the former. After a thickness of 35 mm, the descending

Table 3. Maximum shear stress value of point A when the reinforcement thickness varies

Centroids position	10 mm	15 mm	20 mm	25 mm	30 mm	35 mm	40 mm	45 mm	50 mm
Shear stress (MPa)	0.0353	0.032	0.029	0.0265	0.0244	0.0226	0.0213	0.0199	0.0188

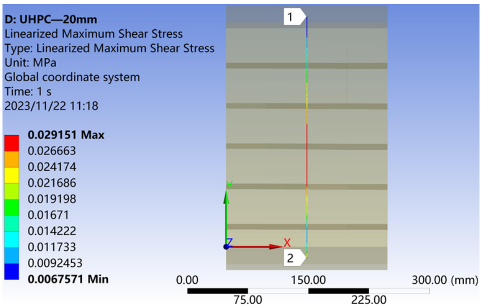

Fig. 6. UHPC reinforcement at the thickness of 20 mm

gradient gradually decreases, which has the best economic characteristics. In summary, it is recommended that the optimal reinforcement thickness in UHPC-RC shear reinforcement system is 35 mm.

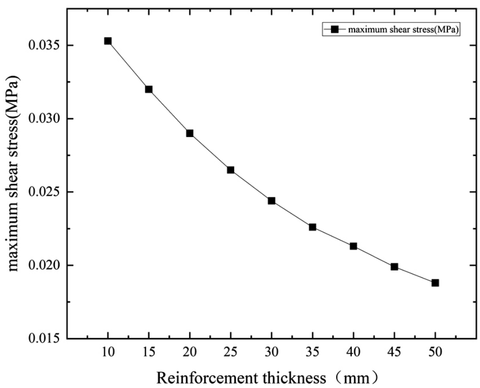

Fig. 7. Curve of maximum shear stress changes with reinforcement thickness

3.3. Effect of reinforcement range on RC beam

In order to determine the optimal reinforcement length, the reinforcement length is set between 500–2500 mm, and a set of finite element models with different reinforcement ranges is established with 500 mm as the parameter. The calculation results and some of the maximum shear stress clouds are shown in Fig. 8, 9 and Table 4.

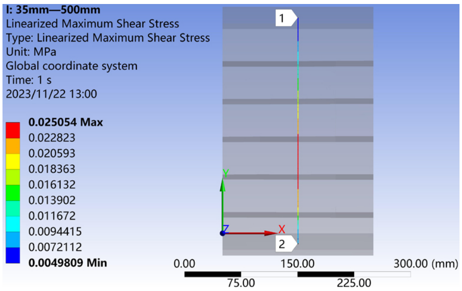

Fig. 8. The reinforcement length at 500 mm

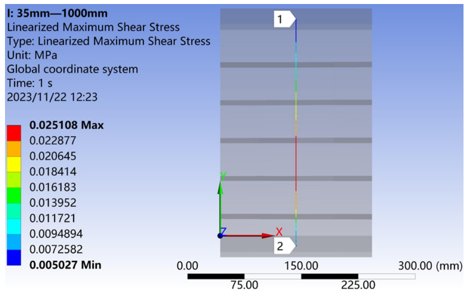

Fig. 9. The reinforcement length at 1000 mm

Table 4. Maximum shear stress value at point A when the reinforcement length varies

Centroids position	500 mm (MPa)	1000 mm (MPa)	1500 mm (MPa)	2000 mm (MPa)	2500 mm (MPa)
Shear stress (MPa)	0.0228	0.0226	0.0228	0.0228	0.0226

From Table 4, it can be seen that the changes of the maximum shear stress value at observation point A remain almost unchanged within the range of 500–2500 mm. This indicates that changing the reinforcement range exerts little effect on the maximum shear stress position of the RC beam, and that considering economic factors, the reinforcement range is taken as 500 mm.

3.4. Influence of reinforcement method on RC beam

In order to determine the influence of reinforcement methods on shear strength, three reinforcement methods are adopted: bottom-double side reinforcement method, double side reinforcement method, and single side reinforcement. The reinforcement length is determined to be 500 mm at the end of the support and the reinforcement thickness is 35 mm; thus, three finite element models with different reinforcement methods are established. Fig. 10– 15 and Table 5 show the maximum shear stress diagram of RC beam when using different reinforcement methods.

Table 5. Maximum Shear stress under Different Reinforcement Methods

Centroid position	Bottom-double side reinforcement	Double-side reinforcement	Single-side reinforcement
Shearing stress (MPa)	0.0228	0.0279	0.0372

According to Fig. 10–15, it can be summarized as Fig. 16. It can be concluded that the maximum shear force values of the observation points for bottom and double side reinforcement are smaller than those for single side reinforcement and double side reinforcement. Therefore, bottom-double side reinforcement is set as the reinforcement plan.

1. Bottom – double side reinforcement

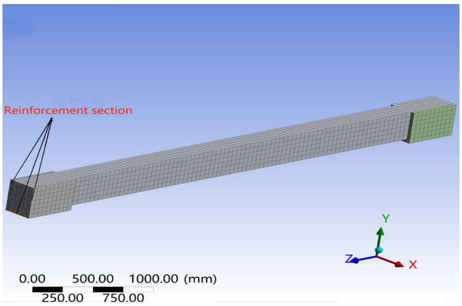

Fig. 10. Bottom - Double Side Reinforcement

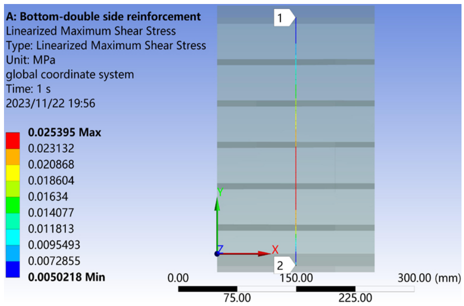

Fig. 11. Bottom surface - double side reinforcement stress diagram

2. Double side reinforcement

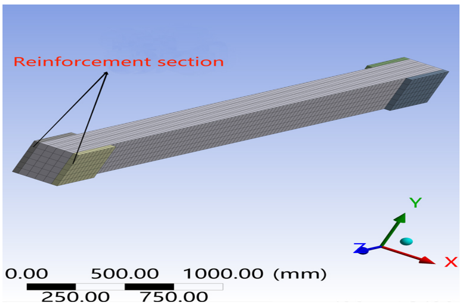

Fig. 12. Double side reinforcement

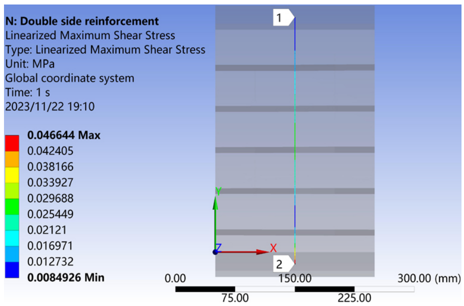

Fig. 13. Stress diagram for double side reinforcement

3. Single-side reinforcement

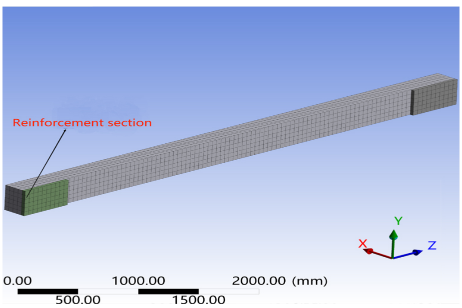

Fig. 14. Single-side reinforcement

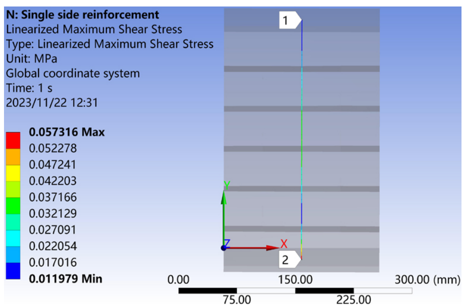

Fig. 15. Stress diagram for single-side reinforcement

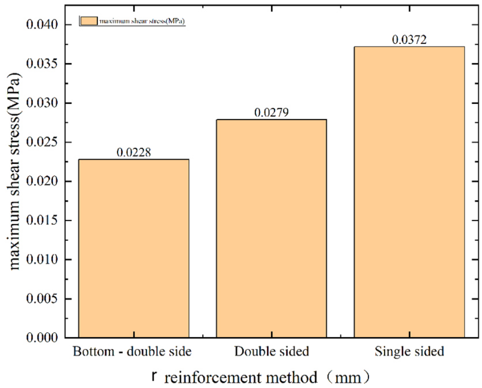

Fig. 16. Graph for maximum Shear stress under Different Reinforcement Methods

3.5. Calculation formula for shear strength of UHPC-RC reinforcement system

The maximum shear stress value of the bottom-double side reinforcement method should be 0.0051 MPa lower than that of the double side reinforcement method. Theoretically, the maximum shear stress value is supposed to be equal to the shear stress value after bottom reinforcement minus 0.0051 MPa.

1. Calculate moment of inertia
   Taking the reinforcement thickness of 40 mm as an example for calculation, and transform the reinforced section according to strength of materials, as shown in the following Fig. 17 and 18.

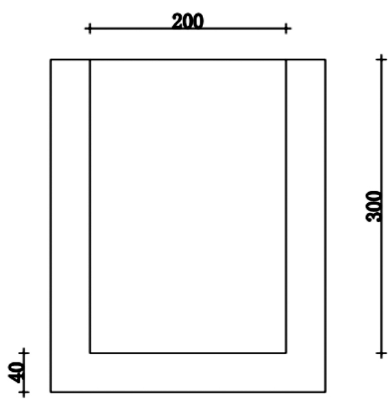

Fig. 17. Cross section before reinforcement

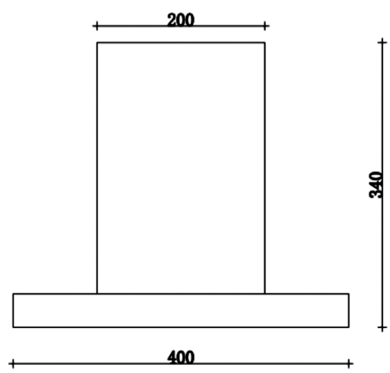

Fig. 18. Cross section after conversion

Neutral axis position after reinforcement:

$$y = \frac{200 \times 300 \times (40 + 150) + 400 \times 40 \times 40/2}{200 \times 300 + 400 \times 40} = 154.21 \text{ mm}$$

Moment of inertia after reinforcement:

$$I = \frac{bh_1^3}{12} + A_1 h_1'^2 + \frac{bh_2^3}{12} + A_2 h_2'^2$$

$$I = \frac{200 \times 300^3}{12} + 200 \times 300 \times 35.79^2 + \frac{400 \times 40^3}{12} + 400 \times 40 \times 134.21^2$$
$$= 81.0 \times 10^7 \text{ mm}^4$$

2. Maximum shear stress of beam body τ:

$$\tau_1 = \frac{F_s}{2I_z}\left(\frac{h^2}{4} - y^2\right) = \frac{1500}{2 \times 81.7 \times 10^7}\left(\frac{340^2}{4} - 35.79^2\right) = 0.0254 \text{ MPa}$$
$$\tau = \tau_1 - 0.0051 = 0.0203 \text{ MPa}$$

In summary, the calculation results of different reinforcement thickness calculation models are shown in Table 6, Fig. 19.

Table 6. Comparison of theoretical shear stress values by computer

Thickness	10 mm	15 mm	20 mm	25 mm	30 mm	35 mm	40 mm	45 mm	50 mm
Computerization (MPa)	0.0353	0.0320	0.0290	0.0265	0.0244	0.0226	0.0213	0.0199	0.0188
Hand calculation (MPa)	0.0332	0.0315	0.0281	0.0251	0.0231	0.0224	0.0203	0.0187	0.0178

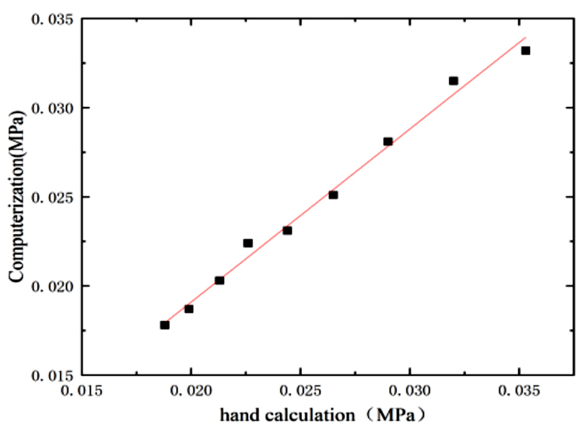

Fig. 19. Fitting Curve of Hand Computation

Due to the almost zero effect of the change in reinforcement length on shear stress, the effect of reinforcement length on shear stress is not taken into consideration; instead, only the theoretical formula for reinforcing the bottom and both sides are taken into account.

The theoretical shear stress value formula obtained from the above fitting curve is as follows, and

$$\tau = 0.9669\left[\frac{F_s}{2I_z}\left(\frac{h^2}{4} - y^2\right)\right] - 0.0002$$

4. Strengthening design of solid bridge

4.1. Project overview

The reinforced bridge is located on a national highway, with a total length of 165 m and a span combination of 8×20 m, the bridge deck width at 12.6 m and a carriageway width at 9.0 m. The upper structure of the bridge is a simply supported T-beam with 7 pieces per span. Completed in 1997, this bridge has an embedded abutment and is designed to bear Class 20 for automobiles; the pier is solid, double column pier, and the pile foundation serves as the pier foundation. Bridge Plan is shown in Fig. 20.

Fig. 20. Bridge Plan

4.2. Calculation results and analysis of the original structure

This article uses Midas Civil to establish a bridge model, takes one span (20 m) of the bridge for modeling, and calculates the stress situation before the reinforcement. The design standard is first-class highway, and the main design parameter is C30 concrete forming the main body of the bridge. The model is established as shown in the Fig. 21.

The original bridge structure is a T-shaped beam, using 8 HRB300 steel bars with a diameter of 32 mm and 2 HRB300 steel bars with a diameter of 20 mm as the main reinforcement, and 2 HRB300 grade steel bars with a diameter of 8 mm and a spacing of 100 mm as the stirrups. Take two HRB300 steel bars with a diameter of 32 mm as the bent-up bar.

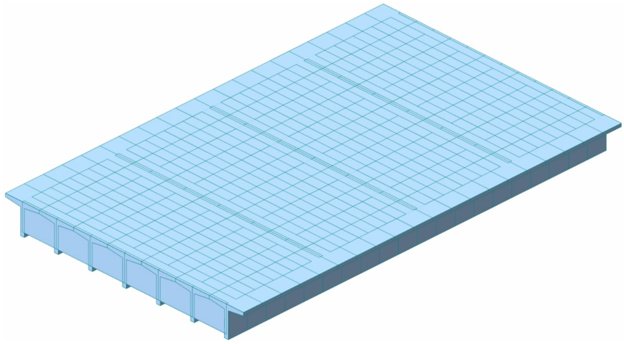

Fig. 21. T-beam finite element model

The reinforcement design of this bridge adopts the UHPC-RC reinforcement system: the thickness of the UHPC reinforcement layer is 3.5 cm, and the outer form work is made of steel plates with a thickness of 6 mm (bottom side – double sides), the reinforcement length 2 m at both ends of the beam, and the height is the height of the beam web. In general, the reinforcement structure is shown in Fig. 22.

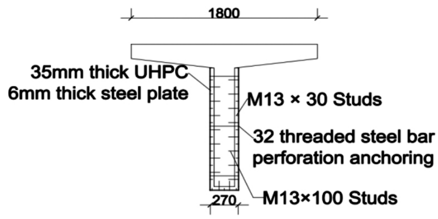

Fig. 22. Schematic diagram of T-beam reinforcement (unit: mm)

According to the provisions of *Design Principles of Concrete Structures* [16], the shear bearing capacity of the above-mentioned T-shaped beam is calculated to be 904.3 kN. According to the calculation formula 5.3.2-2 in the design specification for *strengthening concrete structures using the enlarged section method* [17], the resistance of the reinforced bridge diagonal section is 1149.7 kN. The calculation results of Midas Civil for the basic combined internal force are shown in Fig. 23 and 24.

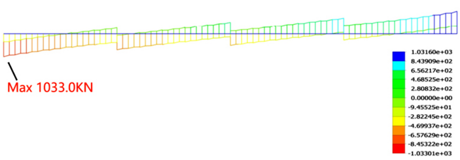

Fig. 23. Shear Envelope Diagram of Basic Composite Lower Beam

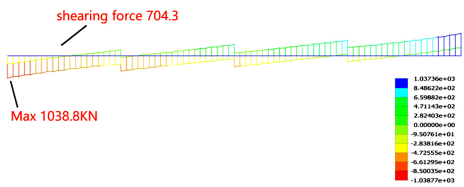

Fig. 24. Shear envelope diagram of the basic composite lower beam after reinforcement

Table 7 shows that the self weight of the bridge after reinforcement has increased to a certain extent. Under the basic combination, the increase in shear force of the main beam is relatively small (0.48%), while the shear bearing capacity of the inclined section has increased by about 27.1%, with a significant increase. The shear force value at the variable cross-section is 704.3 kN, which is less than the shear bearing capacity and meets the requirements for shear bearing capacity.

Table 7. Shear bearing capacity of bridges before and after the reinforcement

Bridge status	Checking location	Design value (kN)	Resistance (kN)
Before the reinforcement	Shear force at oblique section of support	1033.0	904.3
After the reinforcement	Shear force at oblique section of support	1038.8	1149.7

5. Conclusions and outlook

This article completed the establishment of a UHPC-RC shear reinforcement system using parameter analysis methods. The mechanical state of the reinforcement system was analyzed using reinforcement materials, reinforcement thickness, reinforcement length, and reinforcement method as parameters. Then the research results were applied to practical engineering, and the results showed that this reinforcement method can significantly improve the shear bearing capacity of the oblique section of the bridge and improve the stress state of the bridge, with significant reinforcement effects. The main conclusions of this article are presented below.

1. The best UHPC-RC shear reinforcement plan is as this: three sided reinforcement with UHPC material should be used with reinforcement thickness at 35 mm, and reinforcement length at 3000 mm, side reinforcement height at 100 mm.
2. When the reinforcement thickness is 35 mm, the maximum shear stress value of the beam section becomes the optimal taking into the curve changes and economic characteristics into consideration; when the reinforcement thickness arrives at 35 mm, within the reinforcement range of 500–2500 mm, the maximum shear stress value of the beam section does not change significantly with the reinforcement length. When considering economic factors, a reinforcement length of 500 mm is selected. After the comparison of the three reinforcement methods, the bottom double side reinforcement method has the best effect.
3. Applying the research results of this article to the reinforcement design of a bridge with insufficient shear strength, the analysis results show that the reinforcement method can significantly enhance the shear bearing capacity of the oblique section of the bridge without significantly increasing the self weight of the bridge, thus

improving the stress state of the bridge. The reinforcement effect is significant in this case. Besides, this reinforcement method is convenient for construction, and the reinforced steel plate can serve as a template to further control construction costs, making it more practical to be put into use.

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