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Original Paper

Design and Treatment Case Analysis of Continuous T-beam External Prestressed Composite Reinforcement Based on Finite Element Model Calculation

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Abstract

The second section of a highway bridge is a 3×30m prestressed concrete continuous T-beam, of which the 5th span 4# T-beam was found to have multiple structural cracks, such as U-shaped cracks and vertical cracks, during regular inspections after one year of operation. Analysis has shown that this was attributed to the fact that the insufficient prestressing during construction caused inadequate prestressing in the beam body. In this sudy, Midas/Civil software is utilized to establish a spatial finite element model to estimate the loss of prestress in damaged T-beams, yielding results consistent with the inspected conditions. On this basis, an external prestressing reinforcement design plan is proposed. The innovative plan considers the impact of reinforcement on the hogging moment of continuous T-beams and optimizes the layout of prestressed steel strands. The layout and fixing methods of steel turning blocks and anchoring blocks are also optimized in accordance with the stress characteristics of continuous T-beams, with the bearing capacity and safety reserve improved. After checking and analyzing the crack width of the reinforced T-beam, it was found that the plan fully meets the requirements for prestressed concrete Class A components. According to plan, the damaged T-beam was repaired and reinforced, and continuous observation of the reinforced T-beam was conducted for two years. No new development of bridge defects was observed in the later stages, indicating a satisfactory reinforcement effect. This provides technical reference for similar projects.

Keywords

prestressed continuous T-beam, calculation of prestress loss, external prestressing, reinforcement design

1. Introduction

The prestressed continuous T-beam structure is a commonly used structural form in bridge engineering as it boasts advantages such as strong bearing capacity, high construction efficiency, good durability, and low maintenance costs. In the early stages, due to inadequate control of prestress tensioning during construction, the prestress reserve of the beam body was insufficient, leading to occasional decreases in the bearing capacity of the T-beam. In the later stages, under the effect of traffic loads, a large number of structural cracks appeared in the beam body. When the stress performance of the bridge fails to meet the requirements of specification calculations, reinforcement design must be carried out.

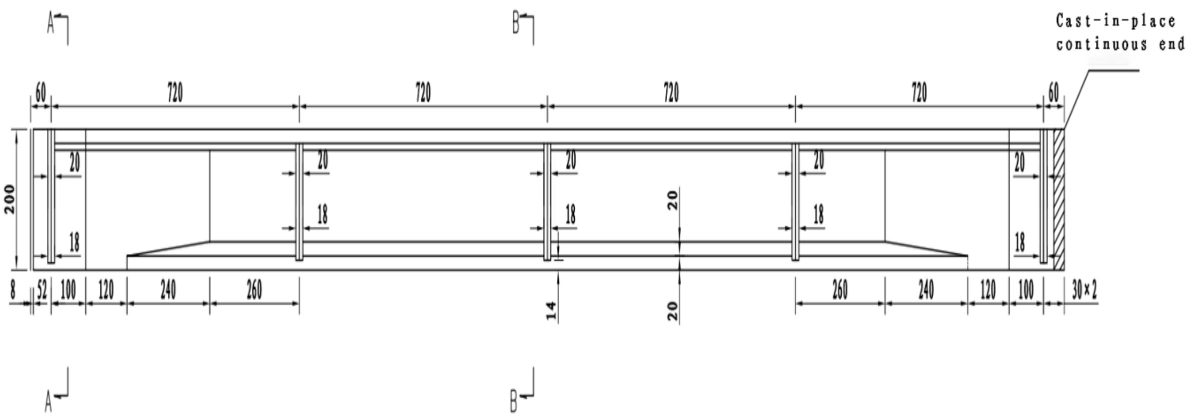
Common reinforcement methods for such issues include enlarging the cross-section, bonding steel plates, bonding fiber-reinforced composite materials, and taking external prestressing reinforcement (CCCC First Highway Consultants Co., LTD., 2008; Gao, Li, Yuan, et al., 2014; Liu, Hu, Gu, et al., 2017). Among all these methods, the external prestressing reinforcement offers flexibility in layout, with minimal operational interference. It cannot only significantly improve structural bearing capacity but also increase structural stiffness and adjust the stress state of the structure, thus widely used in reinforcement projects (Zhang, Zhao, & Meng, 2020). Song W. L. and Song W. B. (2017) conducted research based on the nonlinear analysis theory of external prestressing reinforcement, demonstrating that the use of external prestressing reinforcement can help improve the bearing capacity of prestressed box girder bridges operating with cracks, effectively enhance the overall performance of the bridge, reduce mid-span deflection and crack width, promote the utilization of bridge concrete strength, and achieve ideal reinforcement effects. In recent years, extensive theoretical and experimental research have been conducted on the design and technical optimization of external prestressing reinforcement. Hu and Song (2022), Fu, Hu and Gao (2021), and Gao, Wu, Yue, et al. (2017) studied the layout of external prestressed steel strands and the number of steering blocks, exploring the impact of different layouts on the stress performance of T-beams. Xu, Xu, Ding, et al. (2014) determined the optimal range of prestress levels by comparing the failure conditions of beam bodies under different prestress levels.

Meanwhile, the prestressed carbon fiber plates reinforcement can effectively close bottom cracks, reducing the rate and width of crack. Peng, Shang, Jin, et al. (2008) and Xu, Li, Zhao, et al. (2010) found that it significantly enhances the cracking load, yield load, and ultimate bearing capacity. It is also proved in their study that tensioning the carbon fiber plates can improve material utilization efficiency. Beside, Dou and Liu (2018) and Wang (2017) verified the effectiveness of prestressed carbon fiber plates reinforcement for integral plate bridges and T-beam bridges.

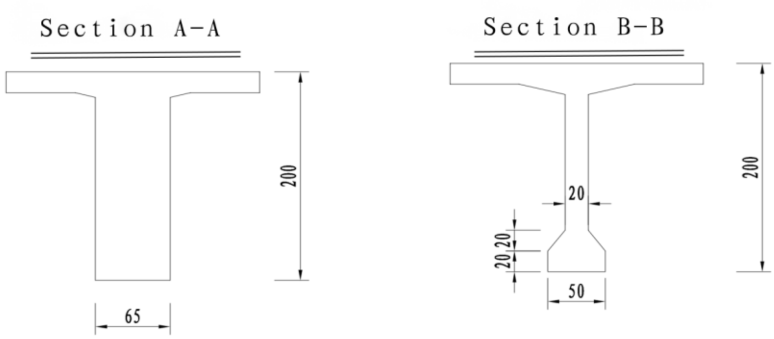
According to the inspection results of a damaged continuous T-beam bridge span, this paper applies Midas/Civil software to establish a spatial finite element model and estimate the loss of prestress in the damaged T-beam. The calculation results are in good agreement with the inspection findings. On this basis, an external prestressing composite reinforcement design scheme is proposed, which combines the use of prestressed carbon fiber plates, external prestressed steel strands, and bonding carbon fiber cloth. After reinforcement, observation for the bridge was conducted for two consecutive years, with no new development of bridge defects founded, demonstrating good reinforcement effects achieved.

2. Engineering Background

A prestressed continuous T-beam bridge spans a river, utilizing a double-deck structure. The left deck of the bridge covers a total length of 697.00m, while the right deck spans 667.00m in total length, with a clear deck width of 2×11.00m. The upper structure of the right deck of the bridge is composed of 6×(3×30m) + 4×30m post-tensioned prestressed concrete simply supported-to-continuous T-beams. The abutments, piers #3, #6, #9, #12, #15, #18, and their bearings employ GYZF4450×86mm type tetrafluoro slide-type rubber bearings, while the bearings for the remaining piers adopt the GYZ450×99mm type laminated rubber bearings. The elevation and cross-section views of the T-beam are presented in Figure 1.



(a) Elevation diagram of T-beam



(b) Plan diagram of T-beam

Figure 1. 30 Meter T-beam Structure

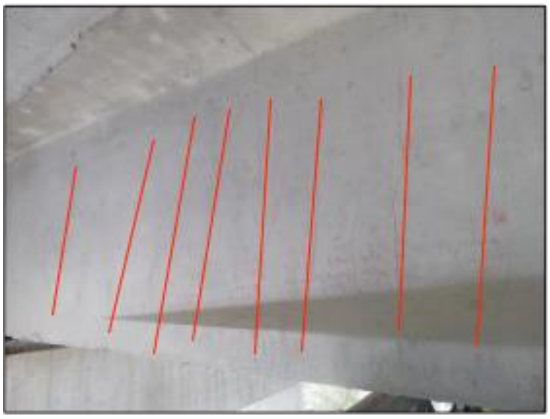
3. Detection and Analysis before Reinforcement

3.1 Detection Results Analysis

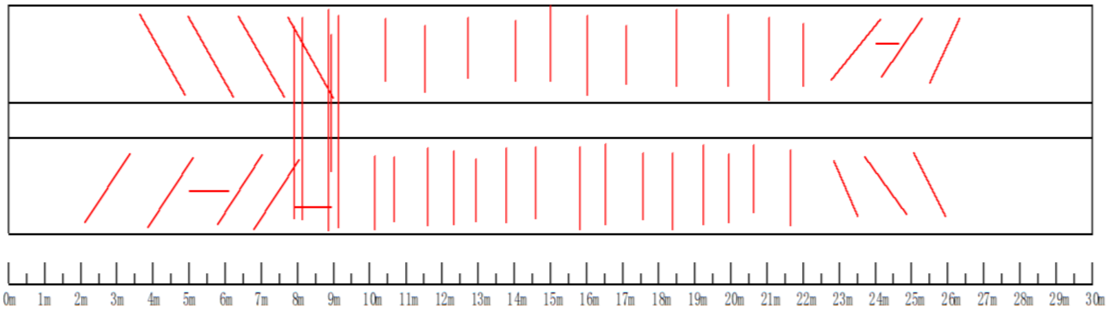
In a regular inspection of the bridge after one year of operation, is was found that in the fifth span of the right deck of the bridge, the 4# T-beam exhibited 26 vertical cracks, 14 oblique cracks, 5 U-shaped cracks, and 3 longitudinal cracks, with widths ranging from 0.04mm to 0.12mm. The vertical cracks were distributed over the section from L/4 to 3L/4 of the T-beam, located on both sides of the web. The oblique cracks were situated near the bearings. If these defects continue to develop, negative impact would be caused to the adjacent T-beams and the entire span, potentially resulting in severe effects on the bearing capacity of the structure.

As a result, a special inspection was conducted on the 4# T-beam in the fifth span of the bridge. Based on the findings of the special inspection, the distribution pattern of the cracks, and a review of the construction documents, it is inferred that during the construction of this bridge span, the prestress tensioning was insufficient, leading to inadequate prestress within the beam body. Under the long-term action of self-weight and vehicle loads, the beam structure deformed as the loads increased. Due to significant prestress losses, the deflection of the T-beam became excessive, resulting in tensile stress on the concrete surface. When the tensile stress on the surface exceeded the tensile strength of the concrete, structural cracks occurred on the surface. Figure 2 illustrates site photos and crack distribution diagram of typical cracks in the T-beam.

(a) Oblique cracks at the end of the beam



(b) Vertical cracks in the mid-span



(c) T-beam cracks

Figure 2. Site Photos of Cracks on T-beam and Crack Distribution Diagram

3.2 Prestress Loss Analysis

3.2.1 Calculation Assumptions

According to the analysis of the detection results, structural cracks appeared in this beam segment due to the insufficient prestress within the beam body. Now, based on the morphology and distribution of the cracks, an estimation of the prestress loss in this beam segment is made, with assumptions that:

(1) The quantity and quality of internal steel strands in the positive and negative bending moment sections of the T-beam meet the design requirements.

(2) The quality of the steel strand anchors and the anchoring of the steel strands in the sagging and hogging moment of the T-beam meet the design requirements.

(3) The concrete and ordinary steel reinforcement material indicators of the T-beam meet the design requirements.

(4) The construction processes such as lifting of the T-beam and the prestress tensioning of the hogging moment comply with the specification requirements.

3.2.2 The Finite Element Model

To accurately analyze the prestress loss in the T-beam, a finite element model was established for the entire upper structure as shown in Figure 3, which consists of 805 nodes and 1374 elements, with elements 234 to 261 as the defected T-beam elements.

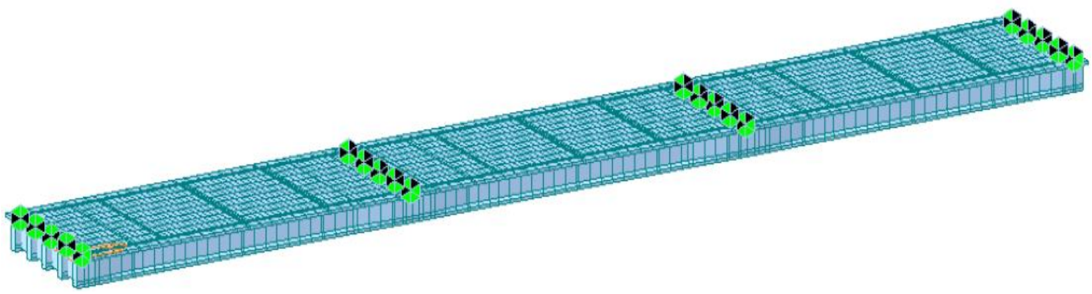


Figure 3. Finite Element Calculation Model of the Upper Structure of Single T-beam

3.2.3 Parameters of Main Materials

Main Beam Concrete: C50

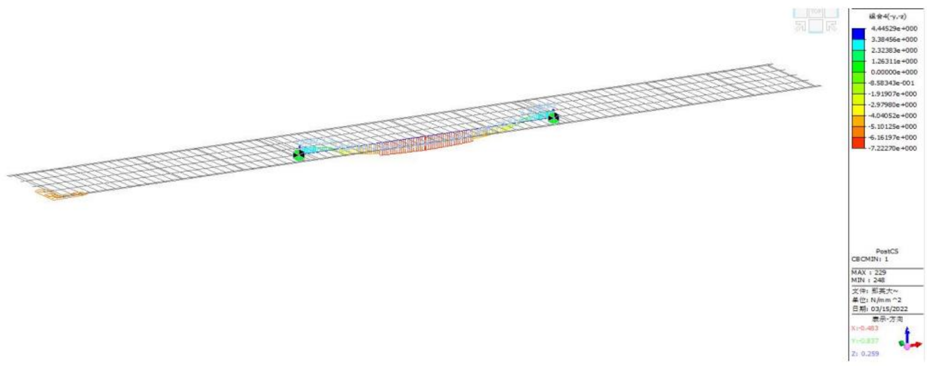
Prestressed Steel Bar: φ15.24mm Steel Strand

The values of various mechanical parameters of the materials are derived from on the *Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts* (JTG 3362-2018). The specific gravity values of the materials can be found in the *General Code for Design of Highway Bridges and Culverts* (JTG D60-2015).

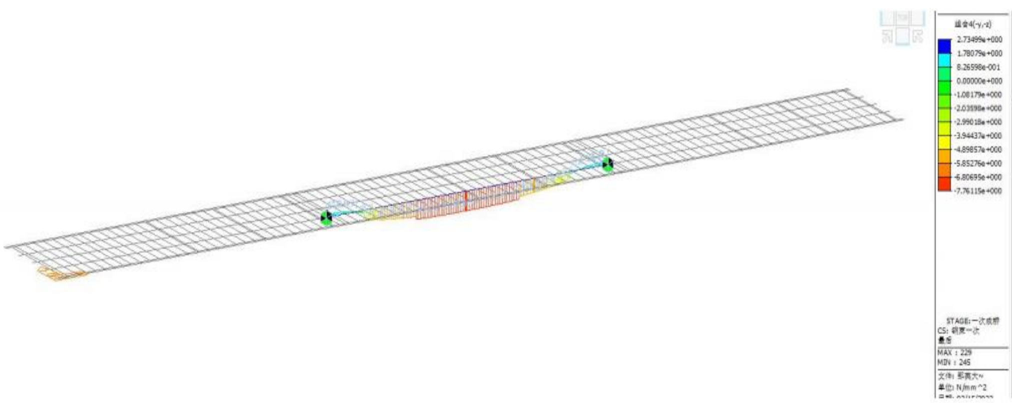
3.2.4 Major Calculation Results

Through analysis and trial calculations, when the prestress of the T-beam, which was reduced by a gradient of 10%, was reduced by 30%, the reserve of compressive stress in the concrete at the lower edge of the T-beam disappeared; When it was reduced by 50%, cracks appeared at a position 4.8m away from the beam end, with a crack width of 0.14mm; When the prestress was reduced by 70%, cracks appeared at a position 9.0m away from the beam end, with a crack width of 0.18mm.

Given the inspection results, combined with the comprehensive consideration of the location and width of the cracks, it can be seen from Table 1 that when the prestress of the T-beam is reduced by 60%, the calculation results are in good agreement with the inspection findings. At that time, the maximum crack width of the T-beam is 0.13mm, and the cracks are located 6.0m away from the beam end. The distribution of normal stress and the stress of the prestressed steel strands in the T-beam are shown in Figure 4.



(a) Normal stress



(b) Stress of the prestressed steel strands (Unit: MPa)

Figure 4. Stress State of the Defected T-beam

4. Maintenance and Reinforcement Plans

4.1 Comparison and Selection of Reinforcement Plans

Plan One: Enhance the safety reserve of the bearing capacity of the T-beam and suppress the development of cracks, using prestressed steel wire rope, high-strength steel wire mesh, and high-performance mortar to make reinforcement. Firstly, the cracks in the T-beam will be repaired and sealed. Secondly, reinforcement will be applied to the horseshoe and web of the T-beam using a prestressed steel wire rope reinforcement layer with a diameter of 4mm and a standard tensile strength of 1670MPa. By installing and tensioning the prestressed high-strength steel wire rope through the prestressed anchorages set at the bottom of the T-beam, the crack resistance, stiffness, and ultimate bearing capacity of the main beam can be simultaneously improved. Additionally, the thickness of the protective layer of the beam will be increased, so that the corrosion resistance of the beam can be improved.

Plan Two: After treating the cracks and concrete defects in the T-beam, this design proposes to reinforce the T-beam by bonding prestressed carbon fiber plates and external prestressed steel strands. Subsequently, carbon fiber sheets will be applied to the web of the T-beam to further restrict the development of cracks and simultaneously enhance the overall stiffness. This technique allows for rapid reinforcement without interrupting bridge traffic. The carbon fiber plates used for reinforcement, as a new material, possess numerous advantages such as light weight and high strength (with a mass density of 0.23 times that of steel bar, minimizing the impact of additional reinforcement loads on the original structure), corrosion resistance, and fatigue resistance (three times stronger than steel reinforcement). Through this active reinforcement technique, the reinforcement materials can participate in the stress bearing of the original structure early on, effectively improving the bending capacity of the reinforced bridge, increasing its stiffness, reducing the width of existing bridge cracks and suppressing their development, so as to enhance the durability of the bridge. Three prestressed carbon fiber plates, with a width of 50mm and a thickness of 2mm, are installed at the bottom of the T-beam, with a total prestress of 90kN. On both sides of the T-beam web, one bundle of prestressed steel strands is installed, extending to the negative bending moment zone of the adjacent span. Each bundle consists of three steel strands, tensioned to 465kN.

The strengths and weaknesses of the two plans as well as the recommendation suggestions are detailed in Table one.

Table 1. Comparison and Selection of Reinforcement Plans

Content for comparison		Plan one	Plan Two
Main reinforcement contents		Prestressed steel wire rope + high-strength steel wire mesh + high-performance mortar reinforcement	Prestressed carbon fiber plate + prestressed steel strands + bonding carbon fiber cloth
Technicality	Design experience	Relatively mature experience	Relatively mature experience
	Construction technology	Mature reinforcement construction technology; rich in	Mature reinforcement construction technology; rich in experience;

		experience; numerous application examples	numerous application examples
	Damages to the original structure	With a large number of fixing nails inserted to fix the anchor seat steel plates and steel wire mesh, causing damage to the original structure	Planting reinforcement for anchoring anchor seat steel plate and steering gear, with a small number of holes for planting reinforcement, causing almost no damage to the original structure
	Reinforcement effects	Able to enhance the crack resistance, stiffness, and ultimate bearing capacity of the beam, increase the thickness of the protective layer, and improve the corrosion resistance of the beam	The prestressed carbon fiber plates can enhance the crack resistance of the beam, while the prestressed steel strands can adjust the stress distribution in the reverse bending moment zone and enhance the safety reserve of bearing capacity, with minimal damage to the original structure.
Economical efficiency		Moderate cost	Slightly higher cost
Major strength		1. Enhancing the bending bearing capacity and safety reserve of the beam. 2. Improving the stiffness and crack resistance of the structure. 3. Improving the corrosion resistance of the beam.	1. Improving the stiffness and crack resistance of the structure and increasing the safety reserve. 2. Enhancing the corrosion resistance of the beam. 3. Barely causing changes to the appearance of the beam. 4. Requiring fewer routine maintenance items after reinforcement. 5. A shorter construction period and minimal impact on traffic. 6. Barely increasing weight and causing minimal damage to the original structure. 7. Representing advanced industry technology.
Major weaknesses		1. Multiple construction steps involved 2. Requiring high material	1. Higher cost. 2. Requiring a high-quality construction team with relevant

	performance 3. Reinforcement layer prone to peeling and detachment due to poor construction quality control	experience.
Suggestion	Comparison	Recommended

According to the result, plan two (Prestressed carbon fiber plate + prestressed steel strand + bonding carbon fiber cloth) is recommended to be applied to the reinforcement of the damaged T-beam.

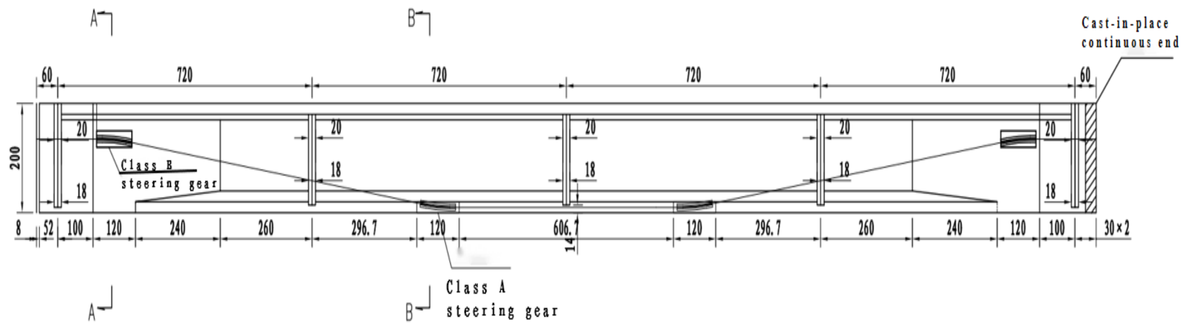
4.2 Reinforcement Approach

According the report on the inspection, numerous vertical cracks have appeared in the web of the 4# T-beam near the mid-span area, which will weaken the stiffness of the main beam, deteriorate the operational conditions of the bridge, and affect the safety of bridge. Moreover, they may still be in a state of continuous development. Therefore, the reinforcement of the 4# T-beam body is achieved by adding longitudinal external prestressed steel strands and prestressed carbon fiber plates, aiming to achieve the following objectives:

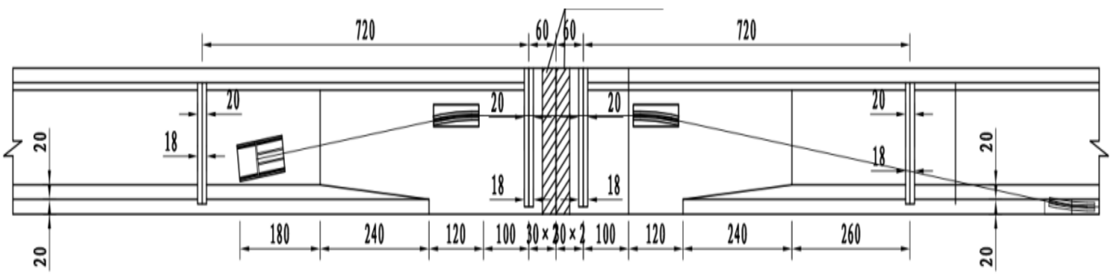
1. Adjust the stress distribution of the beam body through tensioning the external prestress, bringing it closer to equilibrium; improve the structural stress, and restrain the continued downward deflection of the main beam and the expansion of web cracks.
2. Move the T-beam span upwards through the additional tensioning of external prestress, enhancing safety reserves, increasing the compressive stress reserve at the lower edge of the main span's mid-span, improving the state of primary tensile stress, and ensuring that the compressive stress and main compressive stress meet regulatory requirements.

4.3 Deployment of External Prestressed Steel Strands

External prestress are set up on both sides of the T-beam. The newly added external prestress will be effectively connected to the T-beam through the installation of steel steering devices and steel anchoring blocks, with the steel anchoring blocks and steering blocks anchored to the concrete using mechanical anchor bolts. One strand of 3φ15.24mm steel strands are arranged on each side of the web near the T-beam, totaling two. The schematic diagrams for the elevation and cross-section layout of the external prestress are shown in Figures 5-6, and the steering device is depicted in Figure 7.



(a) Elevation layout (sagging moment) (unit: cm)



(b) Elevation layout (hogging moment) (unit: cm)

Figure 5. Elevation of External Prestressed Steel Strands Layout

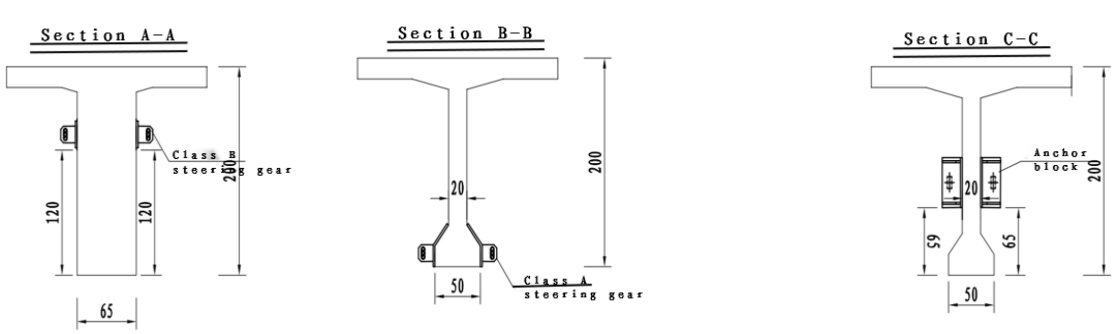


Figure 6. Cross-sectional Drawing of External Prestressed Steel Strands Layout

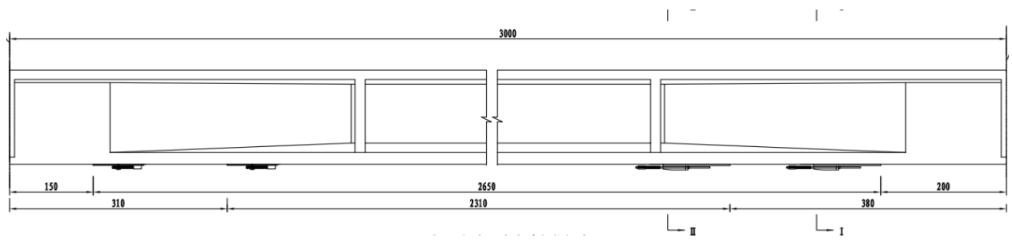
(a) Class A steering devices

(b) Class B steering devices

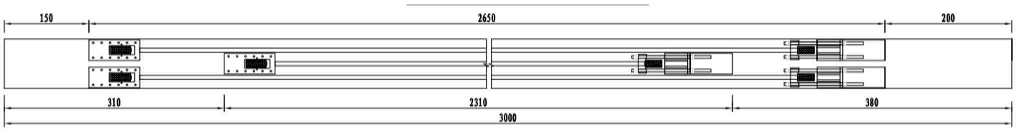
Figure 7. Structural Diagram of Steel Steering Devices

4.4 Prestressed Carbon Fiber Plates on the Bottom of the Beam

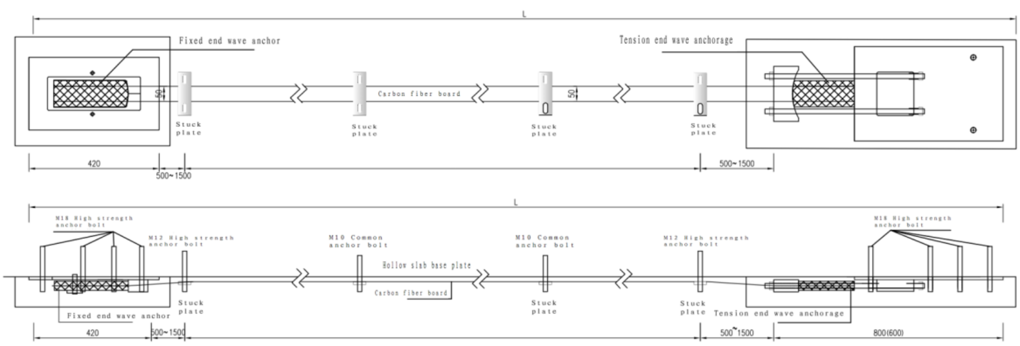
Through experiments, numerical simulations, and engineering examples, it has been demonstrated that bonding prestressed carbon fiber plates to the bottom of T-beams can effectively enhance the flexural bearing capacity of bridges (Wang, Yan, Liu, et al., 2023). Therefore, a reinforcement scheme using prestressed carbon fiber plates is applied on the bottom plate of the T-beam. Schematic diagrams and structural drawings of the elevation and plan layout of the prestressed carbon fiber plates are shown in Figure 8.



(a) Elevation layout of prestressed carbon fiber plates



(b) Plan layout of prestressed carbon fiber plates



(c) Design of Carbon Fiber Plates

Figure 8. Design Drawing for Prestressed Carbon Fiber Plates Reinforcement

4.5 Bonding Carbon Fiber Plates on Vertical Cracks

After sealing the cracks in the T-beam, the method of bonding carbon fiber fabric is applied along the direction of the cracks for treatment, as shown in Figure 9.

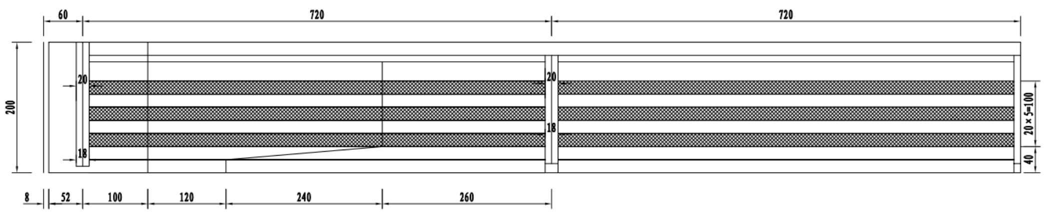


Figure 9. Elevation View of T-beam Web Reinforced with Carbon Fiber Cloth

4.6 Reinforcement Calculation Results

4.6.1 Parameters of Main Reinforcement Materials

Epoxy steel strand: φ15.24mm

Carbon fiber plate: Thickness 3×2.0mm

Width 50.0mm

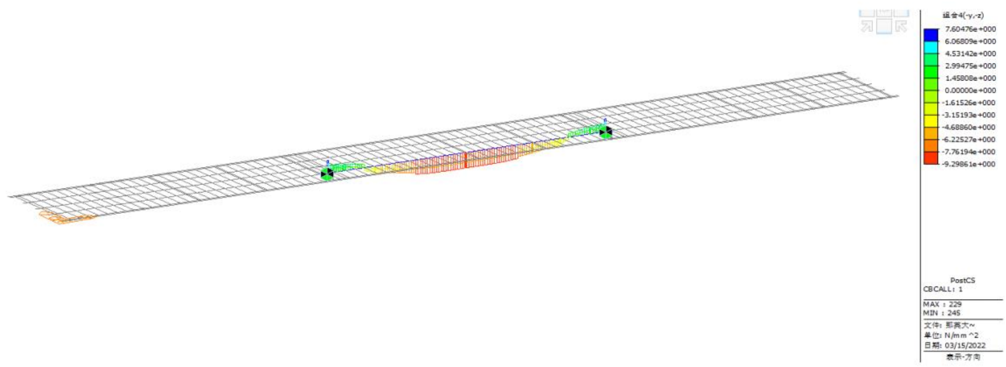
4.6.2 Major Calculation Results

The calculation results suggest that, when reinforcement measures are taken, the prestress has been restored to 53%. The reinforced T-beam meets the requirements for prestressed concrete Class A components. The calculation results are presented in Table 2 and Figure 10.

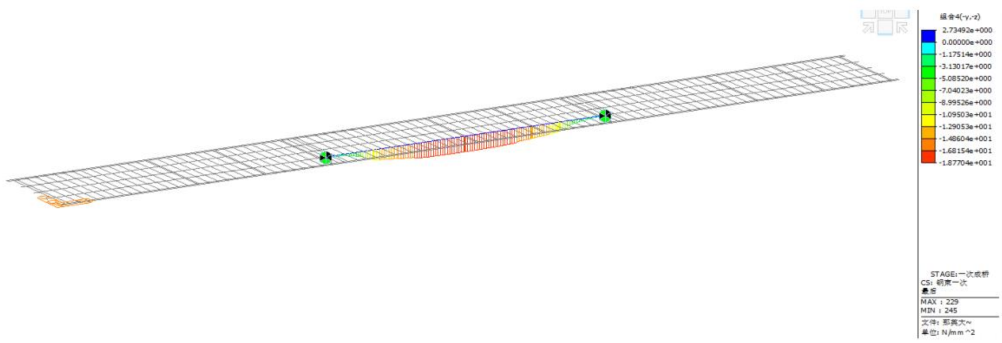
Table 2. Calculation Result of Crack Width after Reinforcement

Unit	Top/Bottom	Result	Sig_T (MPa)	Sig_B (MPa)	Sig_SS (MPa)	W_tk (mm)	W_AC (mm)
[234]	Bottom	OK	11.1	-2.3	-125.0	0	0.1
[235]	Bottom	OK	11.4	-1.1	-274.5	0	0.1
[236]	Bottom	OK	7.7	2.4	0.0	0	0.1
[236]	Bottom	OK	7.7	2.9	0.0	0	0.1
[238]	Bottom	OK	7.4	3.7	0.0	0	0.1
[239]	Bottom	OK	7.0	4.5	0.0	0	0.1
[239]	Top	OK	6.2	6.3	0.0	0	0.1
[239]	Bottom	OK	6.7	5.2	0.0	0	0.1
[240]	Top	OK	6.2	6.4	0.0	0	0.1
[240]	Bottom	OK	6.4	6.0	0.0	0	0.1
[241]	Top	OK	3.2	7.5	0.0	0	0.1
[243]	Top	OK	3.0	8.0	0.0	0	0.1
[244]	Top	OK	2.9	8.3	0.0	0	0.1
[245]	Top	OK	2.8	8.4	0.0	0	0.1
[246]	Top	OK	2.8	8.4	0.0	0	0.1
[247]	Top	OK	2.8	8.4	0.0	0	0.1

[247]	Top	OK	2.8	8.4	0.0	0	0.1
[249]	Top	OK	2.8	8.3	0.0	0	0.1
[249]	Top	OK	2.9	8.2	0.0	0	0.1
[251]	Top	OK	2.9	8.1	0.0	0	0.1
[251]	Top	OK	3.0	7.9	0.0	0	0.1
[253]	Top	OK	3.2	7.4	0.0	0	0.1
[253]	Top	OK	6.1	6.6	0.0	0	0.1
[253]	Bottom	OK	6.5	5.8	0.0	0	0.1
[255]	Bottom	OK	6.8	5.1	0.0	0	0.1
[255]	Bottom	OK	6.8	4.9	0.0	0	0.1
[257]	Bottom	OK	7.2	4.1	0.0	0	0.1
[257]	Bottom	OK	7.6	3.2	0.0	0	0.1
[258]	Bottom	OK	7.8	2.8	0.0	0	0.1
[260]	Bottom	OK	7.7	1.7	0.0	0	0.1
[260]	Bottom	OK	11.5	-1.6	-217.1	0	0.1
[262]	Bottom	OK	11.2	-2.7	-81.2	0	0.1



(a) Normal stress after reinforcement of T-beam (unit: MPa)



(b) Stress of prestressed steel strands after Reinforcement of T-beam

Figure 10. Stress State of Reinforced T-beam

5. Maintenance and Reinforcement Measures

Prior to the implementation of external prestressing reinforcement, fine and dense cracks with a width less than 0.15mm and shallow depth are sealed by crack repair adhesive on the surface and penetrating long cracks with a width greater than or equal to 0.15mm are sealed through pressure grouting with crack repair adhesive or epoxy resin-based grouting materials to restore the overall structural integrity and stiffness. As for defects such as concrete honeycombing, pitted surfaces, cavities, and damages, epoxy mortar are applied for repair (Zhang, Yao, & Yang, 2022).

When tensioning the external prestressed steel strands, the position of prestressed steel strands and stressed steel bars in the original T-beam of the bridge is first determined using a reinforcement protection layer meter. Based on the actual location of the original steel bars and prestressed steel strands at the new anchor blocks and steering blocks, a plan setting-out is performed according to the positions and dimensions of the steel steering devices and anchor blocks provided in the reinforcement construction drawings. On this basis, the installation is then carried out. Subsequently, the newly added external prestressed steel strands for the web are installed in the order of upper rows followed by lower rows. The prestressed steel strands are tensioned in the sequence of from bottom to top, long to short, and symmetric at the beam ends. Finally, the anchor sealing and protective measures are properly implemented.

(a) Site photo upon completion (b) Site inspection photo after 2 years of operation

Figure 11. Site Photos of T-beam Reinforcement upon Completion and after 2 Years of Operation

It took one month to maintain and reinforce the bridge. Currently, it has been in operation for nearly two years. Since the reinforcement, no further development of cracks or emergence of new cracks and other defects have been observed on the bridge. The effect of bridge maintenance and reinforcement is satisfactory. Photographs of the site are shown in Figure 11.

6. Conclusions

(1) A visual and special inspection was conducted on the 4# T-beam of the fifth span of the prestressed concrete continuous T-beam bridge. It is speculated according to the results of the inspection, the distribution of crack patterns, and the investigation of construction materials that insufficient prestress tensioning during construction has led to a lack of prestress within the beam body. As a result, structural defects such as U-shaped cracks and vertical cracks appeared in the mid-span section of the beam body under the action of self-weight and vehicle loads.

(2) An estimation of the loss of prestress was conducted according to the crack patterns and distribution on the 4# T-beam of this bridge span, using the Midas/Civil finite element software. When the prestress of the T-beam is reduced by 60%, the calculation results are consistent with that gained from inspection.

(3) The layout of the prestressed steel strands is optimized, innovatively taking into account the impact of reinforcement on the hogging moment of the continuous T-beam. Adjustments are made to the stress distribution in the hogging moment to enhance the safety reserve of the bearing capacity.

(4) The layout positions and fixation methods of the steel steering blocks and anchor blocks are optimized. Based on the stress characteristics of the continuous T-beam, steel steering blocks are placed near the top of the cast-in-place continuous segment and near the bottom of the T-beam mid-span to facilitate the layout of the external prestressed steel strands in the sagging and hogging moments.

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