Analysis of the flexural performance of Precast Box Girders Reinforced with a combination of Steel-Slab-Concrete Plus Unbonded Prestressing

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ABSTRACT: Due to the serious development of cracks in precast box girders, there is no reliable method to detect the loss of prestress and carry out effective reinforcement of box girders. This paper proposes a reinforcement method of steel plate - concrete with unbonded prestressing, and applies this method to a 30m reinforced concrete prestressed box girder bridge. This paper uses FEA software to carry out a comparative analysis of the load-deflection curve of the reinforced mid-span section by comparing with the conventional bonded steel reinforcement method and the load test data, and through the analysis results, the calculation formula of the flexural load capacity of the steel plate-concrete with unbonded prestressing reinforcement method is derived. The results show that the flexural load carrying capacity of the strengthened mid-span section is significantly improved, and the proposed calculation formulae deviate from the finite element simulation results within 5%, which can be applied to actual projects.

1 Introduction

Reinforced concrete bridges, as time in service increases, structural damage occurs to the bridge structure, the service level decreases and the structural load carrying capacity deteriorates.in order to restore and strengthen the service level and load-bearing performance of the bridge, the bridge structure needs to be reinforced as necessary [1]. Common reinforcement methods include steel plate reinforcement, carbon fibre fabric reinforcement, tensioned prestressing reinforcement and increased section reinforcement [2].

In recent years, many scholars have conducted experimental and theoretical studies on different strengthening methods. Nie Jianguo [3]and others proposed the method of steel plate-concrete combination reinforcement, and conducted experimental studies on the mechanism of force transfer and deformation for steel plate-combination reinforced reinforced concrete combination beams [4], which showed that the method could substantially improve the beam cross-sectional load carrying capacity and flexural stiffness; it had a good control effect on cracks. Jin Hui and Xu Yue [5]proposed a combined steel-concrete strengthening technique to solve the problem of "single-slab stress" in assembled hollow-core bridges, and the static load tests before and after strengthening showed that the method could enhance the transverse connection between the main beams and effectively solve the problem of "single-slab stress". The method can enhance the transverse connection between the main beams and can effectively solve the problem of "single slab bearing", and the ultimate flexural capacity calculation formula was derived for RC beams damaged by suitable reinforcement after strengthening [6]. Wang Chunsheng et al. [7] investigated the flexural load bearing performance of prestressed concrete small box beams and hollow slab beams reinforced with steel plate - concrete combination using footing tests, and derived the formulae for calculating the flexural ultimate load bearing capacity of footing test beams based on the plastic damage mechanism of the test beams.

In summary, in view of the fact that cracks develop more severely in some of the box girders during operation and that there is no reliable method to accurately detect the loss of prestress, the reinforcement method of steel plate - concrete with unbonded prestress is proposed in order to ensure the service level and load carrying performance after strengthening. This paper uses finite element software to carry out simulations, analyse the mechanical behaviour, analyse the deflection and strain in the span and derive the formulae for calculating the flexural load capacity of this strengthening method.

2 Reinforcement solutions

The bridge was designed in 2009 with a design load of Highway-I. The superstructure is made of precast box girders. The bridge mainly has serious U-shaped cracks

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and transverse cracks at the bottom of the slab, which are caused by the large difference between the pre-stressing degree of the box girder and the design theoretical value during construction and use, and the tensile stress of the concrete at the lower edge of the box girder exceeds the tensile strength of the concrete during use, resulting in concrete cracking. The cause of this disease is caused by poor construction control.

In view of the serious development of cracks in the bridge and the absence of a reliable method to detect the prestressing force, a steel plate-concrete plus unbonded prestressing reinforcement was adopted, which consisted of planting anchor bolts in the bottom plate and web of the box girder, installing a U-shaped steel plate sleeve, keeping a gap of 8 cm between the steel plate sleeve and the concrete of the box girder, filling the gap with self-levelling concrete, setting six linear The unbonded prestressing strands are anchored at the ends of the additional concrete. A cross section of the box girder reinforcement span is shown in Figure 1.

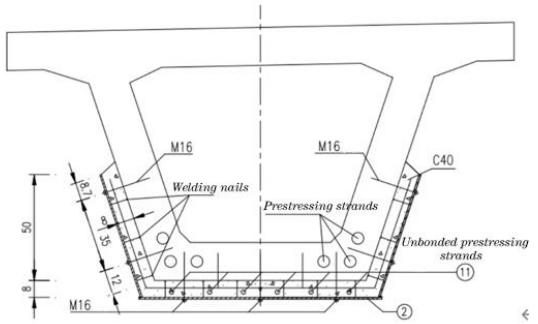

Figure 1. Box girder reinforcement span cross-section

3 Analytical FE models

In order to accurately simulate the effect of the reinforcement, Diana is used to establish a solid structural model, define the corresponding material ontological model and load loading mode, set up a suitable non-linear analysis in the analysis, and then simulate the structural effect of the bridge reinforcement for analysis.

3.1 Entity modelling

In order to compare the reinforcement effect of the combined reinforcement plus unbonded prestressing method, a model of a box girder with a top slab width of 2.4m, a bottom slab width of 1m and a height of 1.6m was established according to the actual dimensions, and a solid unit model was built using the steel plate paste method and the combined reinforcement plus unbonded prestressing method respectively. The thickness of the steel plate is 8mm, the reinforcement is embedded steel and the prestressing strand is 15.2mm prestressing strand. The force situation at the interface between the different structures in the reinforced structure is complex and a key issue in the finite element simulation. The bond-slip interface between the concrete and steel plate interface is treated by meshing and the model is established [8], as shown in Figure 2.

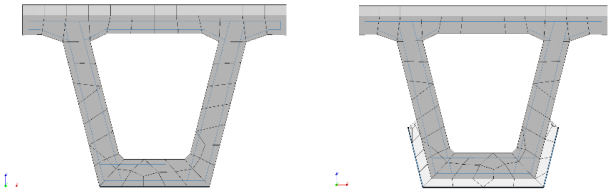

Figure 2. Finite element model diagram (glued steel plate left, unbonded combined reinforcement right)

3.2 Material Ontology Modeling

3.2.1 Concrete material models

In the finite element modelling analysis, the material instantonal relationship plays a crucial role in the calculation results[9-10]. In order to improve the calculation accuracy of the simulation results, the total strain cracking model is used for the concrete principal structure relationship, which can simulate the mechanical behaviour and crack distribution during the whole process of concrete cracking and damage more accurately. The principal structure model has exponential softening in tension and parabolic characteristics in compression, and the crack angle will produce constant changes with the update of the stress, always perpendicular to the direction of the main tensile stress, ensuring the main strain and main stress of coaxiality and no shear locking will occur, as shown in Figure 3.

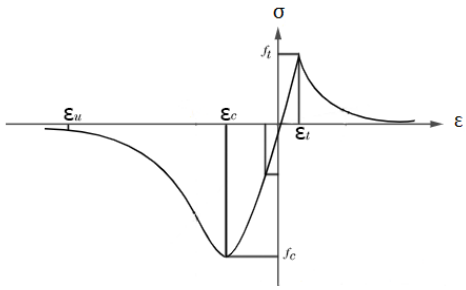

Figure 3 Constitutive Relation Diagram of Concrete

3.2.2 Reinforcing steel material model

The Tresca and Von Mises plasticity criteria are used for the intrinsic reinforcement relationship. the Tresca model considers that yielding occurs when the maximum shear stress reaches a certain limit value, as shown in equation 1, the Von Mises model considers the effect of intermediate principal stresses on the yielding of the material, with the yielding condition shown in equation 2.

$$f(\sigma,k)=|\sigma_1-\sigma_2|-\bar{\sigma}(\kappa) \tag{1}$$

$$f(\sigma,\eta,\kappa)=\sqrt{3J_2}-\bar{\sigma}(\kappa)=\sqrt{\frac{1}{2}(\sigma-\eta)^T P(\sigma-\eta)}-\bar{\sigma}(\kappa) \tag{2}$$

4 Numerical analysis

4.1 Loading Mode

The analysis in this paper establishes a finite element model of a 30m span prestressed concrete simply supported box girder. In order to test the combined reinforcement unbonded method, the model is simulated by static loading according to previous research and experiments by scholars[11], one third of the span cross section is selected for loading, three equal points of the bridge deck width are selected for loading, the loading schematic is shown in Fig.4. So, the loading point is used to simulate the role of loading mat stone on the steel bar, and the restraint is applied at the same time at the pivot point position of the girder end to achieve the simulation of the simple support restraint.

Figure 4 Finite element loading diagram

4.2 Numerical simulation results

The finite element load-span deflection curves are shown in Fig. 5. The 2 curves are divided into non-cracking elastic phase, cracking elastic phase and plastic development phase. It can be seen that: at the initial stage of loading, the strengthening effect of the unbonded prestressed plus steel plate concrete combination reinforced beam and anchor bonded steel plate reinforced beam on the concrete beam is not significant due to the effect of stress hysteresis. with the increase of load, the reinforced steel plate and the original beam reinforcement jointly bear the load, and the load carrying performance and ultimate load carrying capacity of the reinforced beam are significantly improved.

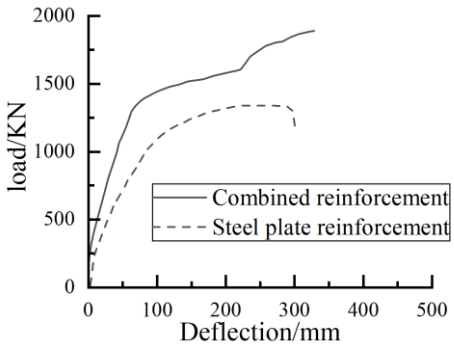

Figure 5 Load-deflection curve diagram

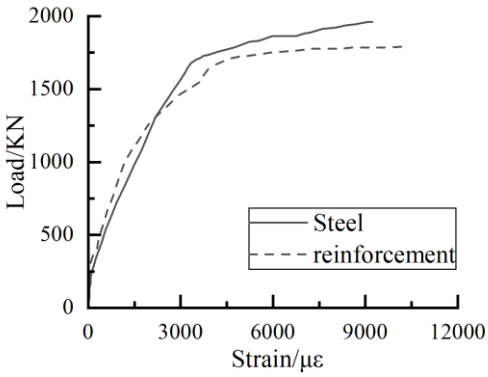

Figure 6 Load-strain curves diagram

As shown in Fig. 6.The development of the strain in the steel plate and the strain in the main reinforcement of the original beam can be divided into three stages. Stage 1 is the pre-cracking stage, where the strain in the steel plate and the strain in the reinforcement are low and not very different, and the reinforced beam is in the elastic stage. Stage 2 is the stage between the cracking of the concrete and the yielding of the main reinforcement of the beam, where the strain in the steel plate at the lower edge of the beam increases slightly faster than the strain in the reinforcement, and both have the same growth trend. Stage 3 is the stage between the yielding of the reinforcement and the ultimate damage of the test beam.

5 Bending capacity formula

Considering that when the structure is reinforced by such a combination of reinforcement methods, the concrete and steel required for reinforcement generate new self-weight loads and the concrete structure is subjected to secondary forces; according to (GB50010-2010) and previous theoretical studies on concrete structures as well as experimental studies, when carrying out the theoretical concrete flexural load capacity analysis and establishing the equilibrium equations for the calculation of the load capacity formula, it is necessary to follow Some basic assumptions[12].

(1)Flat section assumption: the concrete structure section remains flat before and after deformation.

(2) Good adhesion between the new and old concrete and between the steel plates and the new concrete, with no relative slip.

(3) The steel plates on the bottom and sides of the combined reinforcement do not reach the design value of tensile strength, and the tensile effect of the concrete is not considered.

(4) The reinforcement principal relationship is ideal elastic-plastic.

(5) The prestressing strand is reliably anchored until the ultimate load carrying capacity is reached and it is assumed that the stress in the unbonded prestressing strand is equal to the tension control stress when the prestress is applied.

With reference to (GB50367-2013), the thickness of the steel plate used in the reinforcement is 8mm, which is small compared to the height of the original structure and the thickness of the new concrete poured during the reinforcement, so the influence of the thickness of the reinforced steel plate is ignored; at the same time, the formula for calculating the flexural bearing capacity of the positive section of this reinforcement method is deduced

from the contents of the code, which can be calculated according to the following formula, Structure as shown in Fig. 1:

$$f_c bx + f_{sy}^{'} A_{sy}^{'} = f_{sy} A_{sy} + \sigma_p A_p + f_{py} A_{py} + \varphi_{sp} f_{sp} A_{sp} + 2T_{spw} \tag{3}$$

$$M_u = f_{py} A_{py}\left(h_{py} - \frac{x}{2}\right) + f_{sy} A_{sy}\left(h_{sy} - \frac{x}{2}\right) + \varphi_{sp} f_{sp} A_{sp}\left(h - \frac{x}{2}\right) + \sigma_p A_p\left(h_p - \frac{x}{2}\right) + 2T_{spw}\left(h_{sp} - \frac{x}{2}\right) + f_{sp}^{'} A_{sp}^{'}\left(\frac{x}{2} - a_s^{'}\right) \tag{4}$$

where: σ_p :tress values for unbonded prestressed reinforcement; f_{sp} :Yield stress values for steel plates on the underside of reinforced steel plates; f_{py} : tensile strength values of prestressed steel bars in the original structure; T_{spw} : Reinforced steel plate side tension; A_p : Area of unbonded prestressed reinforcement; A_{sp} : Area of reinforced steel plate underside plate; A_{py} : Area of prestressed steel in original structure; φ_{sp} : Discount factor for the design value of the tensile strength of the bottom plate when considering the effect of secondary forces.

$$\sigma_p = E_p \varepsilon_p \tag{5}$$

$$\varphi_{sp} = \frac{\left(0.8\varepsilon_{cu}\left(h - \frac{1}{2}t_{sp}\right)\Big/x\right) - \varepsilon_{cu} - \varepsilon_{sp}}{f_{sp}/E_{sp}} \tag{6}$$

$$T_{spw} = \int_0^{h_{sp}} \sigma_y b_y dy \tag{7}$$

As shown in Table 1, the load carrying capacity results obtained by applying equation (4) are less different from the finite element calculation values. Therefore, the load carrying capacity of the unbonded prestressed-combined reinforced concrete box girder can be assessed by applying the theoretical equations obtained from the analysis in this section.

Table 1. Table of calculated load carrying capacity values

Calculation method	Theoretical formulae	Finite element calculated values
Calculated values $(KN \cdot \mathrm{m})$	14392	14879

6 Conclusions

The following conclusions are based on the research in this paper:

(1)The steel-hybrid combination reinforcement method is optimised from a passive reinforcement method to an active reinforcement method by applying unbonded prestressing, and the integrity of the reinforced structure is significantly enhanced.

(2)The unbonded prestressed combination reinforcement method can increase the cross-sectional area, increase the moment of inertia of the cross-section and the cross-sectional stiffness, which can effectively reduce the load-induced deflection and reduce the deformation.

(3)This paper establishes a simplified formula for calculating the flexural load carrying capacity of the positive section of unbonded prestressed combined reinforced box girder based on the simulation results, the calculation results have less error with the finite element calculation results, and can be used to calculate the flexural load carrying capacity of reinforced concrete box girder.

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