Stress analysis of continuous rigid bridge reinforced by extracorporeal prestressing

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Abstract. For the force performance of continuous rigid bridge reinforced by in vitro prestressing. Firstly, the structural characteristics of continuous rigid bridge and the principle of in vitro prestressing technology are introduced, and then the basic methods of force analysis are elaborated. Then, the bending capacity of the normal section and the shear capacity of the diagonal section of the extracorporeal prestressing reinforced flexural members are calculated, and key parameters such as the ultimate stress value of the extracorporeal prestressing tendons and the ultimate distance of the steel beams to the edge of the compression zone of the cross-section are analysed. Finally, the problems and challenges in engineering practice are discussed and the future development direction is proposed.

Keywords: continuous rigid bridge, extracorporeal prestressing, stress analysis, opportunities and challenges.

1 Introduction

With the increasing traffic load and the continuous impact of environmental erosion, the structural safety and functional durability of continuous rigid bridges, as a form of bridge commonly used in urban expressways and highways, are facing serious challenges. Based on these challenges, experts and scholars in the bridge engineering field have developed a series of reinforcement techniques with the aim of extending the service life of bridges and ensuring traffic safety, among which the extracorporeal prestressing technique has proved to be a very effective means of reinforcement. The extracorporeal prestressing technique improves the mechanical properties of existing bridge structures by applying additional prestressing, especially in improving the cracking and bending resistance, showing unique advantages. Unlike conventional in-built prestressing, extracorporeal prestressing can be applied flexibly to all parts of the bridge with less impact on the structural integrity of the original structure. In addition, this technology is also applicable to bridge structures that are already diseased or damaged, providing a cost-effective solution for the maintenance and rehabilitation of older bridges.

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In the past decades, there have been many studies in China on the effectiveness of extracorporeal prestressing technique and reinforcement of continuous rigid frame bridges. For example, Lv Hongkui [1] proposed an effective reinforcement scheme by investigating the reinforcement design for the chipping of the bottom plate of a continuous rigid-frame bridge for a heavy-duty railway. The studies by Haonan Ding [2] discussed the technical details of extracorporeal prestressing reinforcement of continuous rigid-frame bridges from the theoretical and engineering application perspectives, respectively. In addition, since the force performance of continuous rigid bridges is closely related to their structural health status, any application of reinforcement techniques needs to be based on a full understanding of the bridge force performance. Deng Shufei et al. [3] verified the effectiveness of extracorporeal prestressing reinforcement using finite element software combined with load tests. He Shirong et al. [4]mainly analyzed the structural stress change and vertical deformation, so as to ensure that the bridge reinforcement construction process stress change and its deformation control can achieve the desired effect. Cao Zijun et al. [5] developed and verified the effectiveness of an extracorporeal prestressing reinforcement scheme through the disease analysis of a continuous rigid bridge. Ladislav Klusáček et al [6]showed that transverse prestressing plays a significant role in the rehabilitation of masonry arch bridges. Antonino Recupero, et al[7] Exploring the role of unbonded prestressing tendons in bridge reinforcement through case studies. These literatures provide valuable theoretical and data support for the study in this paper.

An in-depth discussion of the application of extracorporeal prestressing technology in continuous rigid bridges can provide a scientific theoretical basis and technical guidelines for bridge engineering. At present, although extracorporeal prestressing has been applied in a certain number of reinforcement projects, there is a lack of systematic research on the specific effect and optimisation method of extracorporeal prestressing under different engineering environments and various design requirements. Therefore, the aim of this paper is to evaluate the effect of extracorporeal prestressing on the reinforcement effect of continuous rigid frame bridges under different conditions through accurate stress analysis, so as to optimise the reinforcement design and guide the practical engineering application.

2 Basic Theory and Methodology

2.1 Structural characteristics of continuous rigid bridge

Continuous rigid bridge is a type of bridge widely used in modern bridge engineering, which is especially suitable for urban viaducts and highway bridges with its good integrity and adaptability. This type of bridge usually consists of multiple spans arranged continuously, which can effectively reduce the bearing reaction force and improve the structural stress state. However, subjected to traffic loads and environmental factors for a long time, continuous rigid frame bridges often suffer from cracks, deformations and other diseases, which affect their safety and service life.

2.2 Principle of extracorporeal prestressing

Extracorporeal prestressing reinforcement is a method of reinforcing structural members or the whole structure by using externally pre-stressed steel ties or section steel braces, the main principle of which is to use prestressing means to force the added part of the force to change the distribution of the original structural internal force and to reduce the stress level of the original structure. This reinforcement method can completely eliminate the unique stress-strain hysteresis phenomenon in the traditional reinforced structure, significantly improve the structural bearing capacity and crack resistance, and effectively improve the stress state of the structure. Extracorporeal prestressing is not a single structure, but a system containing the following contents: anchoring device, steering device, vibration damping device, extracorporeal steel beam, orifice pipe and slurry. At present, according to the sequence of slurry injection, it is divided into bonded extracorporeal prestressing system and unbonded extracorporeal prestressing system. A schematic diagram of the prestressing bundle arrangement outside the box girder body is shown in Figure 1.

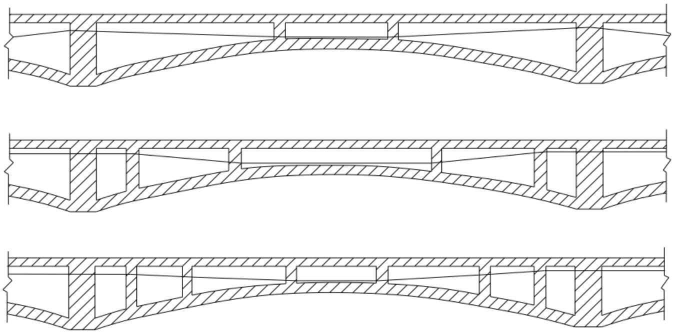

Fig. 1. Schematic diagram of outer beam arrangement of box girder body

The main difference between the principle of extracorporeal prestressing reinforcement and the traditional built-in prestressing reinforcement lies in the location of the prestressing tendons and their adhesion to the soil mix. In the case of in vitro prestressing reinforcement, the prestressing tendons are set on the outside of the soil structure and may be connected to the structure only at the anchorage and turning blocks, so that their stresses are determined by the overall deformation of the structure. In the case of in vivo bonded prestressing reinforcement, the prestressing tendons are located in the interior of the soil structure, completely bonded to the structure, and coordinated with the deformation of the structure at any cross-section, so the stress of the tendons is closely related to a certain concrete cross-section. In addition, extracorporeal prestressing reinforcement technology has been widely used in the reinforcement of old bridges in recent years due to its features of convenient construction, economical and reliable, and the prestressing tendons (more) can be individually anticorrosive or even can be replaced. Numerous engineering practices have proved that the use of extracorporeal prestressing reinforcement of old bridges can significantly improve the structural bearing capacity and crack resistance effectively improve the stress state of the structure.

2.3 Basic methods of force analysis

In the stress analysis of continuous rigid bridge, the finite element method is usually used for detailed simulation. This method provides detailed information on the stresses, strains and deformations of the structure under various loads. The modelling usually includes steps such as material property definition, geometric model creation, boundary condition setting, load application, and resultant analysis. The finite element analysis can accurately predict the improvement effect of reinforcement measures on the stress performance of the bridge and provide a scientific basis for the reinforcement design. Literature 2 used the spatial analysis of large-scale finite element software ABAQUS and its comparison with the simplified stress analysis given by the planar beam cell model established by MIDAS software respectively, to verify the effectiveness of the finite element method in extracorporeal prestressing reinforcement.

3 Analysis of force performance

In the calculation of extracorporeal prestressing reinforcement of curved concrete beams, the key is to calculate the ultimate state of the load capacity, including the bending capacity of the normal section and the shear capacity of the diagonal section [2]. The design value of the ultimate stress of the extracorporeal prestressing steel bundle and the ultimate distance from the bundle to the edge of the compression zone of the cross-section reflecting the secondary effect of extracorporeal prestressing are the keys to the calculation of the bending capacity of extracorporeal prestressed concrete beams.

3.1 The value of ultimate stress of extracorporeal prestressing tendons

When calculating the flexural bearing capacity of an in vitro prestressed reinforced bridge, the ultimate stress σ_{pu} of the horizontal prestressing tendon is a key parameter for calculation. Existing studies show that the ultimate stress of the in vitro prestressing strand is understood to be composed of two parts, namely, the effective prestressing force and the increment of ultimate stress. The Technical Specification for Unbonded Prestressed Concrete (JGJ 92-2004) [8] stipulates that the formula for calculating the value of σ_{pu} for unbonded reinforcement is as follows:

$$\sigma_{pu} = \sigma_{pe} + \Delta\sigma_p \tag{1}$$

$$\Delta\sigma_p = \left(240 - 335\varepsilon_0\right)\left(0.45 + 5.5\frac{h}{l_0}\right) \tag{2}$$

$$\varepsilon_0 = \frac{\sigma_{pe}A_p + f_y A_s}{f_c b h_p} \tag{3}$$

And the stress design value should be satisfied: $\sigma_{pe} \le \sigma_{pu} \le f_{py}$.

Equation: σ_{pe}—Effective stress portion of unbonded prestressing tendons (net of prestressing losses); $\Delta\sigma_p$—Stress increment part of unbonded prestressing tendons; ε_0 —Comprehensive reinforcement indicators; l_0 —Calculated spans for flexural members;h—Height of the section of a bent member; h_p —Distance from the centre of shape of the reinforcement to the edge of the compression zone.

"The Guide to the Design of Extracorporeal Prestressed Concrete Bridges" [9] uses a large number of model tests to obtain regression values and corrects them using a non-linear finite element full-process analysis method to arrive at the following formula for the ultimate stress of an extracorporeal prestressing steel bundle: [10]

For simply supported girder bridges:

$$\sigma_{pu,e} = \frac{1}{1.25}\left[\sigma_{pe,e} + a\left(2.25 - \frac{22}{L/h_{p,e}}\right) \bullet \left(407 - 1048\rho_p - 531\omega^2 + 492\omega\right) - 92\right] \tag{4}$$

For continuous girder bridges:

$$\sigma_{pu,e} = \frac{\left\{\sigma_{pe,e} + 0.92\left[a\left(2.25 - \frac{22}{L/h_{p,e}}\right) \bullet \left(407 - 1480\rho_p - 531\omega^2 + 492\omega\right) - 92\right]\frac{L_1}{L_2}\right\}}{1.25} \tag{5}$$

$$\rho_p = \frac{A_{p,e}\sigma_{pe,e} + A_{p,i}\sigma_{pe,i}}{A_c f_{ck}^0} \tag{6}$$

$$\omega = \frac{A_{p,i} f_{pk,i}^0 + A_s f_{sk}^0}{A_{p,i} f_{pk,,i}^0 + A_{p,e} f_{pk,e}^0 + A_s f_{sk}^0} \tag{7}$$

Equation: L—Calculated span of the beam; L_1—The length of the part of the member to which the load is applied; L_2 —Full length of the component; ρ_p —Prestressing reinforcement indicators; ω—Body tensile reinforcement ratios; $A_{p,e}$ —Cross-sectional area of in vitro prestressing tendons; $A_{p,i}$—The cross-sectional area of the prestressing tendons in the body; $\sigma_{pe,i}$ —Permanent prestressing of prestressing tendons within the beam; $\sigma_{pe,e}$—Permanent prestressing of prestressing tendons outside the beam body; A_c—Concrete cross-sectional area of the beam; f_{ck}^0 —Standard value of concrete compressive strength; $f^{0}_{pk,i}$ —Standard value of tensile strength of prestressing tendons in a beam; A_s —Cross sectional area of longitudinal tensile reinforcement in the body of the beam; f^{0}_{sk} —Standard value of tensile strength of longitudinal tensile reinforcement in beams; $f^{0}_{pk,c}$ ——Standard value of tensile strength of prestressing tendons outside the beam body.

The limiting distance of the steel bundle to the edge of the compression zone of the section can be calculated by the following formula:

$$h_{pu,e} = \eta\gamma\left(1.29 - 0.006\frac{L}{h_{p,e}} - 0.746\frac{S_d}{L} + 0.483\omega^2 - 0.469\omega\right)h_{p,e} \le h_{p,e} \tag{8}$$

η —Correction factor for secondary effects in continuous girder bridges; γ —Correction factor for secondary effects of segmental segmental beams; S_d —Calculate the spacing of steering structures at the cross section.

3.2 Calculation of bending capacity of reinforced member in positive section[11]

This is shown in Figure 2, Referring to the "Design Code for Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" (JTGD62-2004), the box-shaped cross-section is equivalent to T-shaped or I-shaped cross-section for calculation, and the calculation formula is as follows:

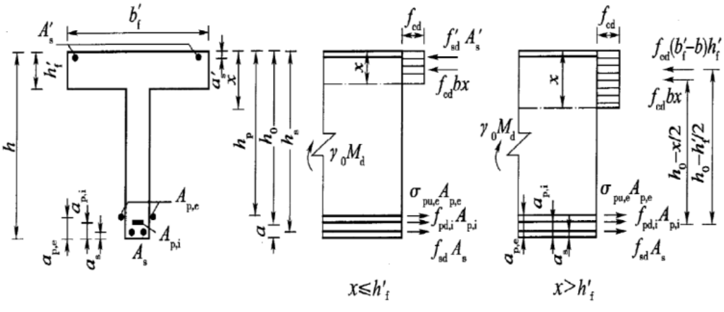

Fig. 2. Illustration of the calculation of the flexural capacity of a positive section of a flexural member

(1) Rectangular cross-section or neutral axis on a flange plate of T-shaped or I-shaped cross-section($x \le h'_f$).

$$\begin{aligned} & f_{cd} b_f' x + f_{sd}' A_s' = \sigma_{pu,e} A_{p,e} + f_{pd,i} A_{p,i} + f_{sd} A_s \\ & \gamma_0 M_d \le f_{cb} b_f' x \left(h_0 - \frac{x}{2} \right) \end{aligned} \tag{9}$$

(2) Neutral axis in the web of a T-shaped or I-shaped section($x > h_f'$).

$$\begin{aligned} & f_{cd} b x + f_{cd} \left(b_f' - b \right) h_f' + f_{sd}' A_s' = \sigma_{pu,e} A_{p,e} + f_{pd,i} A_{p,i} + f_{sd} A_s \\ & \gamma_0 M_d \le f_{cd} b x \left(h_0 - \frac{x}{2} \right) + f_{cd} \left(b_f' - b \right) h_f' \left(h_0 - \frac{h_f'}{2} \right) + f_{sd}' A_s' \left(h_0 - a_s' \right) \end{aligned} \tag{10}$$

The height x of the cross-sectional pressure zone shall be satisfied:

$$\begin{aligned} & x \le \xi_b h_s or x \le \xi_b h_p \\ & x > 2a_s' \end{aligned} \tag{11}$$

Equation: γ_0 —Bridge structural importance factor; M_d —Calculate the design value of the section bending moment; $A_{p,e}$ —Horizontal extracorporeal prestressing bundle cross-sectional area; $\sigma_{pu,e}$ —Ultimate stress of in vitro prestressing bundles; $A_{p,i}$ —Cross-sectional area of prestressing bundles in the original girder; $f_{pd,i}$ —Design value of tensile strength of prestressing bundles in the original girder; A_s —Cross-sectional area of ordinary reinforcement in the tension zone in the original beam; A_s' —The cross-sectional area of ordinary reinforcement in the compression zone in the original girder; f_{sd} —Design value of tensile strength of ordinary reinforcement in the tensile zone in the original girder; f_{cd} —Design value of concrete compressive strength; b_f' —Effective width of the stressed wing plate; b—Web thickness; h_f' —Wing thickness; h_s —Common reinforcement in the original girder body to the top surface of the girder between the discrete; h_p —Departure of prestressing reinforcement in the original girder to the top surface of the girder; h_0 —In vivo and in vitro prestressing bundles and ordinary reinforcement combined position to the top surface of the girder spacing. $h_0 = h - a$; a—Position of prestressing bundles and ordinary reinforcement combined in the tension zone in vivo and in vitro to the distance from the lower edge of the girder; $a_s^{'}$ ——Spacing from the location of the common reinforcement ensemble in the compression zone to the top surface of the beam; ξ_b —Height of the original beam relative to the pressure zone.

3.3 Calculation of shear capacity of inclined section of flexural member strengthened by in vitro prestressing

Calculation of shear capacity of inclined section Eq:

$$\gamma_0 V_d \leq 0.65\times10^{-3} C_1 \beta\lambda\phi \frac{\sqrt{f_{cu,k}}\left(C_2+P\right)bh_0}{m} + 0.75\times10^{-3}\frac{C}{s_v} f_{sv} A_{sv} +$$

$$0.75\times10^{-3} f_{pd,i}\sum A_{pd,i}\sin\theta_i + 0.95\times10^{-3}\sigma_{pe,e}\sum A_{pd,e}\sin\theta_e \tag{12}$$

V_d —Combined design value of the shear force at the shear end of an inclined section; β —Construction method impact factor; λ —In-vivo and out-of-vivo prestressing reinforcement influence factors; ϕ —Cross-sectional shape influence coefficients; $f_{cu,k}$ —Concrete Strength Rating;P—Longitudinal reinforcement ratio;b、h0—are the width of the web and the effective height of the section, respectively;m—Shear span ratio; s_v —Spacing of hoops within diagonal cracks; f_{sv} —Design value of tensile strength of hoop bars; A_{sv} —The total cross-sectional area of each limb of the hoop within one pitch of the diagonal crack; $f_{pd,i}$ —Design value of tensile strength of prestressing tendons in the body; $A_{p,i}$ —Cross sectional area of linear prestressing tendons in the body; $A_{pd,i}$ —The cross-sectional area of the pre-stressing tendon bent up in vivo within the diagonal crack; θ_i 、 θ_e —are the angles between the in-body and out-body bent up prestressing tendons and the beam axis, respectively; $A_{p,e}$ —Cross sectional area of linear prestressing tendons in the body; $A_{pb,e}$ —Cross-sectional area of prestressing tendons bent up outside the body within the diagonal crack;C—Horizontal projected length of an oblique crack.

4 Opportunities and challenges in development

4.1 Technical difficulties

(1) Design of prestressing reinforcement: For extracorporeal prestressing reinforcement, the design needs to accurately understand the structural and force characteristics of the bridge to ensure the effectiveness of the reinforcement. However, in practice, the lack of sufficient historical data or insufficient understanding of the existing bridge conditions may lead to errors in the design of prestressing reinforcement.

(2) Characteristics of prestressing materials. Prestressing materials have their own unique mechanical properties, such as non-linearity and temperature sensitivity, which increase the difficulty of accurate analysis of their stressing behaviour. Especially in complex environmental conditions, such as temperature changes, corrosion, etc., the performance of prestressing materials has a greater impact.

(3) Structural stress redistribution: in the process of extracorporeal prestressing reinforcement, it may cause stress redistribution in the structure. This requires detailed calculations and analyses of the stress on the whole structure to avoid structural damage due to stress concentration or excessive stress.

(4) Load-bearing capacity assessment after reinforcement: The assessment of load-bearing capacity of a reinforced bridge is a complicated issue. In addition to the need to consider the load-bearing capacity of the reinforcement material itself, it is also necessary to consider its contribution to the whole structure. This requires an in-depth understanding of the structural integrity and material properties.

(5) Control during construction: Extracorporeal prestressing reinforcement usually involves large equipment and complex processes. During construction, how to precisely control the application and maintenance of prestressing force and how to ensure the stability of the reinforced structure are challenges in engineering practice.

(6) Problems of project management: In actual projects, there may be problems such as poor management and inadequate supervision, which affect the quality and effectiveness of extracorporeal prestressing reinforcement. For example, the aging of materials and improper maintenance of equipment may affect the reinforcement effect.

4.2 Future Development Direction

(1) the application of new materials: with the progress of science and technology, a variety of new materials continue to emerge, such as carbon fibre composite materials, high-strength stainless steel and so on. These new materials have the advantages of light weight, high strength, corrosion resistance, etc., and can be used for in vitro prestressing reinforcement to improve the bearing capacity and durability of bridges.

(2) the application of new technologies: such as 3D printing technology, intelligent sensor technology, etc., in vitro prestressing reinforcement has great potential for application. For example, 3D printing technology can be used to manufacture prestressing tendons to achieve customised and rapid construction; intelligent sensors can be used to monitor the stress state of the bridge and the relaxation of prestressing, to achieve real-time monitoring and and early warning.

(3) Intelligent and automated: with the development of artificial intelligence and machine learning technology, the monitoring, reinforcement and maintenance of bridges can be intelligent and automated. For example, through machine learning algorithms, the damage situation of the bridge can be automatically diagnosed and the reinforcement programme can be proposed; through robotics, the automatic repair and reinforcement of the bridge can be achieved

5 Conclusion

The force analysis of extracorporeal prestressed reinforced continuous rigid bridge has important engineering significance in extending the bridge life. Through the research of this paper, the bending load capacity and shear load capacity of extracorporeal prestressed reinforced continuous rigid bridges can be clearly grasped, which lays the theoretical foundation for further extending the service life of bridges. However, in engineering practice, there are still some technical difficulties to be overcome, such as the ultimate stress value of prestressing tendons and the ultimate distance of the edge of the compression zone need to be further studied. The future development direction should focus on improving the reliability, economy and durability of the extracorporeal prestressing reinforcement technology, specifically, it should focus on the selection of extracorporeal prestressing tendon materials, the application of new technologies, the study of anti-corrosion technology and intelligent monitoring, etc., to promote the wide application of extracorporeal prestressing technology in the actual engineering.

Funded Projects

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Yunnan Province Science and Technology Specialist Program in 2023 (ZX20230180).

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