Layout and Optimization of the External Prestressing Tendons of Hybrid Beam Rigid Frame Bridges

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Abstract. External prestressing tendon systems can be set to alleviate the problem of excessive mid-span deflection of hybrid beam rigid frame bridges in the long-term use. Based on the Anhaiwan Bridge in Quanzhou of Fujian province, the effects of external prestressing tendons on reducing the deflection of the main span and improving the stress of concrete sections were studied by the shell-solid finite element models. Then the effects of the external prestressing tendons in the steel beams and the concrete beams were analyzed respectively. The effects of each prestressing tendon were further calculated. The final optimized layout was obtained by these studies, which can be used as a design reference for the external prestressed tendons of the hybrid beam rigid frame bridge. Finally, the deflection of the steel beam of the hybrid beam rigid frame bridge was analyzed under the impact of long-term effects such as shrinkage and creep. The comparative analysis of the different tensioning schemes for the external prestress tendons was carried out in order to provide a reference for the operation and maintenance management of the bridges.

Keywords. Hybrid beam rigid frame bridge, external prestressing tendons, layout, optimization.

1. Introduction
The hybrid beam rigid frame bridge takes use of a section of steel beam to replace the concrete beam in middle of the main span. As a result, the span can be larger than the traditional concrete rigid frame bridge. Besides, the problems including the cracks and the excessive deflection in midspan can be alleviated to some extent [1-2]. The application of hybrid beam rigid frame bridge is still in the development stage in China. There are few engineering examples, such as the Double-Line Bridge of Shibanpo Changjiang River Bridge in Chongqing, the Oujiang River Bridge in Wenzhou, the Xiaolan Waterway Bridge in Zhongshan, Yushan Bridge in Zhousan and so on. The Anhaiwan Bridge in Quanzhou is under construction while expected to be completed by June, 2020.

The prestressing tendon systems, consisting of tendons in the top flanges, bottom flanges and webs are set in the long-span prestressed concrete rigid frame bridges in order to reduce the tensile stress of concrete beam and increase the span [3]. With the development of the external prestressing tendons, the scheme of mixing the internal and external tendons has been the mainstream design method in long-span prestressed concrete rigid frame bridges. It is obvious that the supplementary tension and changes of the external prestressing tendons are convenient. Therefore, reliable vertical and longitudinal pre-pressure can be provided and the cracks and the excessive deflection in midspan can be effectively restrained [4]. The external prestressing tendons can effectively control the mid-span deflection of long-span continuous rigid frame bridge [5]. It can also perform as important role in the shear behavior in long-span continuous rigid frame bridge [6]. There are specific methods for using

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the external prestressing tendons in the reinforcement of highway bridges [7]. The concrete beams with the external prestressing tendons exhibit different mechanical properties under long-term effects [8].

As the hybrid beam rigid frame bridge is the optimization of the concrete beam rigid frame bridge, the scheme of mixing the internal and external tendons has become popular. The main purpose of arranging the external prestressing tendons is to solve the problem of excessive mid-span deflection that is common in long-span continuous rigid frame bridges. Thus, the durability and safety of structures can be guaranteed. The layout scheme of the external prestressing tendons in the Double-Line Bridge of Shibanpo Changjiang River Bridge in Chongqing can be a reference in overall design [9]. Based on the Oujiang River Bridge in Wenzhou, some optimization schemes were implemented [10]. Furthermore, the design ideas of the external prestressing tendons in the Xiaolan Waterway Bridge in Zhongshan were discussed [11].

The role of external prestressing tendons in the traditional long-span concrete rigid frame bridges and the layout of the external prestressing tendons in hybrid beam rigid frame bridges were emphatically researched. However, the specific effects and the optimization layout of the external pressing tendons in hybrid beam were neglected. Therefore, the effects and the reasonable layout were analyzed based on the external prestressing tendons of the Anhaiwan Bridge in Quanzhou. It can be a reference for the design of similar bridges.

2. Outline of Engineering
The Anhaiwan Bridge is a three-span hybrid beam rigid frame bridge, with spans of (135 m+300 m+135 m) and a total length of 570 m. The general arrangement is shown in figure 1. The length of steel box beam section for lifting is 103 m in mid-span, with the weight of 1272 t. The length of the steel-concrete combining section is 5 m. It would be closed in March 26th, 2020, and the world's second largest span hybrid beam rigid frame bridge by then. The upper and lower bridge is divided, with a full width of 33.5 m. The height of the main beam sections is 4.5 m~15 m, and the height of the steel box beam sections is 4.535 m~5.869 m. The height of beam section on the middle pier is 15 m, so the ratio of height to span is 1:20; the height of the beam section in middle of the span is 4.5 m, so the ratio of height to span is 1:66.15. The section height changes according to the quadratic parabola. The middle piers take use of the double thin wall piers, with a height of 22.89 m.

![Figure 1. General arrangement of the Anhaiwan Bridge (unit: mm).](image)

The prestressing tendon system of the Anhaiwan Bridge mixes the internal and external tendons. The layout of the external prestressing tendons is shown in the figure 2. In general, it can be divided into two parts: the external prestressing tendons in the concrete beams and the tendons in the steel box beams. A total of 8 pairs of external prestressing tendons are set, with a total specification of 18Φs15.2 tendons for each strand, which are symmetrically distributed along the centerline of the beams.
Figure 2. Layout of the external prestressing tendons in the Anhaiwan Bridge (unit: mm).

The external prestressing tendons along the longitudinal bridge could be divided into 12 parts, which were coded as 1~12 tendons. Among them: No. 1 is eight strands of tendons with 18Φs15.2; No. 2 is six strands of tendons with 18Φs15.2; No. 3 is four strands of tendons with 18Φs15.2; No. 4 is two strands of tendons with 18Φs15.2; No. 5~8 are two strands of tendons with 18Φs15.2; No. 9 are two strands of tendons with 18Φs15.2; No. 10 are four strands of tendons with 18Φs15.2; No. 11 is six strands of tendons with 18Φs15.2; No. 12 is eight strands of tendons with 18Φs15.2. The external prestressing tendons would be only tensioned to 30% of the tension control stress (558MPa) when completed.

3. Analysis of the Effects of the External Prestressing Tendons

3.1. Analytical Method

According to the design of the Anhaiwan Bridge, the shell-solid finite element model for the whole bridge was established. The concrete box beams, steel box beams and tendons were simulated by SOLID95 elements, SHELL181 elements and LINK10 elements, respectively. The total number of the elements was 6×105. The whole model is shown in figure 3.

Figure 3. Shell-solid finite element model of the Anhaiwan Bridge.

3.2. Total Effects of the External Prestressing Tendons under Design Layout

First of all, the deflection of the steel box beam under the dead load is shown in figure 4. It is obvious that the deflection of the middle sections is large while the deflection of the end sections is small. The maximum deflection is 641.78 mm, while the minimum deflection is 429.20 m.

Figure 4. Deflection of steel beam under self-weight (unit: mm).
Under the dead load, the stress distribution of some concrete box beam sections is shown in figure 5. The top flange of section is subjected to tension while the bottom flange is subjected to compression. The section stress closer to the section near middle pier is greater. The maximum compressive stress of the sections near the pier is 17.55 MPa, while the maximum tensile stress is 18.35 MPa. The maximum compressive stress of the sections in middle of the concrete beam is 15.58 MPa, while the maximum tensile stress is 10.01 MPa. The maximum compressive stress of the steel-concrete combining sections is 13.12 MPa, while the maximum tensile stress is 3.87 MPa.

![Stress diagrams of concrete beam sections under self-weight (unit: mm)](image)

(a) Sections near the middle pier
(b) Sections in the center of concrete beam in middle span
(c) Sections near the steel-concrete connection

**Figure 5.** Stress diagrams of concrete beam sections under self-weight (unit: mm).

Taking the effects of the expressing tendons into consideration, the deflection of the steel beam in the middle of span was 628.72 mm and the deflection of the steel beam in the end of span was 421.23 mm. Compared with the calculation results under dead load, the application of external prestressing could effectively reduce the deflection of the steel beam in the middle and end by 13.06 mm and 7.97 mm, respectively. In addition, the external prestressing tendons could reduce the section stress of the general concrete beams. The compressive stress of the bottom flange decreased by 0.20~0.30 MPa, and the tensile stress of the top flange decreased by 0.80~1.00 MPa.

3.3. **Local Effects of the External Prestressing Tendons**

Since the external prestressing tendons were mainly composed of the tendons of the concrete beam and the tendons of the steel beam, the two were applied to the main beam separately to further analyze the contribution of the two parts.

(1) The external prestressing tendons of the concrete beam

On the basis of the initial layout of the external prestressing tendons, the tendons of the steel beam were removed, and only the tendons of the concrete beam were retained, including No. 1~7 and No. 9, 10 tendons. The layout in detail is shown in figure 6.
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Figure 6. Layout of the external prestressing tendons in concrete beams.

Under the combined action of the dead load and the external prestress, the deflection of the steel beam in the middle and end decreased by 9.73 mm and 9.40 mm, respectively, which accounted for 74.50% and 117.94% of the total effects of the external prestressing tendons.

Besides, compared with effects of the all external prestressing tendons under design, the reduction of the compressive stress of the bottom flange of the concrete beam was reduced, and the reduction of the tensile stress of the top flange was increased. These changes were beneficial to the stress of the beam.

(2) The external prestressing tendons of the steel beam

Based on the initial layout of the external prestressing tendons, the tendons of the concrete beam were removed, and only the tendons of the steel beam were retained, including tendons No. 8, 11 and 12. In order to ensure the effectiveness of the prestress, the tendons were extended into the steering block of the concrete beam closest to the steel beam. The specific layout is shown in figure 7.

Figure 7. Layout of the external prestressing tendons in steel beam.

The results showed that when only the external prestressing tendons of the steel beam were applied, the deflection of the steel box beam in the middle decreased by 3.31 mm. However, the deflection in the end increased by 1.48 mm. At the same time, the compressive stress of the bottom flange of the general concrete beam decreased, while the tensile stress of the top flange increased. For the sections near the joints, the tensile and compressive stress increased to some extent. These changes were harmful to the stress of the beam.

The total material amount of external prestressing tendons under the initial layout was 2.95 m3. The total volume of the tendons of concrete beam was 1.65 m3, accounting for 56%; while the total volume of the tendons of steel beam was 1.30 m3, accounting for 44%. For the effects of reducing the deflection of the steel beam, the tendons of the concrete beam contributed 75%, while the steel beam partially contributed 25%. Moreover, the external prestressing tendons of the concrete beam can improve the stress of the concrete beam to a certain extent. Therefore, comparing the material amount with the actual contribution, there is no doubt that it is more economical and effective to set external prestressing tendons in concrete beam.

Considering the bending moment distribution of the hybrid beam rigid frame bridges, when the ratio of the length of the steel beam to the length of the main span is 0.36 (108 m/300 m=0.36), the concrete beam of the main span is mainly subjected to negative bending moments under the dead load. But the steel beam is mainly subjected to positive bending moments. Due to the use of steel beam, the positive bending moments in the middle of the span is small. Thus, the external prestressing tendons in the concrete beam could more effectively reduce the deflection of the steel beam.
According to the above analysis, the application of the external prestressing tendons could reduce the deflection of the steel beam to a certain extent, especially the deflection in the middle. The layout of the external prestressing tendons should be prioritized in concrete beam to further develop the economics and effectiveness of the tendons. The external prestressing tendons near the combining section helped to increase the compressive stress and made the steel-concrete combination tighter. So, the No. 8 and No. 11 tendons were retained and anchored to the combining section. The initial optimized layout is shown in Figure 8.

![Figure 8. Initial optimization of layout of the external prestressing tendons.](image)

### 3.4. Effects of Every External Prestressing Tendon

In order to further analyze the role played by each external prestressing tendon, three tendons shown in Figure 9 were taken and modeled separately to analyze the effects of No. 1, No. 5 and No. 9 tendons. The deflection results are shown in Table 1.

![Figure 9. Layout of the external prestressing tendons for analysis.](image)

| Group     | Deflection under dead load | Difference value with dead load |
|-----------|---------------------------|---------------------------------|
|           | Middle | End   | Middle | End   |
| No tendon | 641.78 | 429.20 | /      | /     |
| No.1 tendon | 633.50 | 422.46 | 8.28   | 6.74  |
| No.5 tendon | 642.04 | 429.23 | -0.26  | -0.03 |
| No.9 tendon | 644.19 | 430.60 | -2.41  | -1.40 |

Notes: the positive value indicates deflection.

As is shown in Table 1, under the action of No. 1 tendon, the deflection of the steel beam in the middle and end is reduced by 8.28mm and 6.74mm, respectively. The compressive stress of the bottom flange of the sections near the middle pier is reduced, and the tensile stress of the top flange is significantly reduced. Under the action of No. 5 tendon, the deflection of the steel beam in the middle and end increased by 0.26mm and 0.03mm, respectively. The maximum compressive stress near the middle sections of the concrete beam increased a little. Under the action of No. 9 steel beam, the deflection of the steel beam in the middle and end increased by 2.41mm and 1.40mm, respectively. The stress of the concrete beam is basically unchanged. It can be seen that the No. 1 tendon which is
parallel to the top of the beam has the best effects on improving the deflection. The external prestressing tendon which is parallel to the bottom of beam increases the deflection. The main reason is that the layout of the tendons is diagonally upward in the concrete beam.

4. Optimization of the External Prestressing Tendons

4.1. Optimization

Through the local analysis of the external prestressing tendons, it can be found that it is more economical and effective to arrange the tendons in the concrete beam. Thereby the initial optimized layout was obtained as shown in figure 8. Further taking the No.1, No.5 and No.9 tendon as an example for the stress analysis, the tendons in the concrete beam could be divided into three parts: tendons parallel to top flange, diagonal tendons and tendons parallel to bottom flange. The tendons parallel to top flange namely the No. 1~4 tendons could reduce the deflection of steel beam and improve the stress of concrete beam. The diagonal tendons namely the No. 5~8 tendons were beneficial to the stress of concrete beam. However, the tendons parallel to the bottom flange namely the No. 9~11 tendons were harmful to the reduction of the deflection of the steel beam. Therefore, on the basis of the initial optimized layout, the tendons parallel to the bottom flange in the concrete beam were removed, that is, the steel beams 1 to 8 were retained. The final optimized layout is shown in figure 10.

![Figure 10. Optimal layout of the external prestressing tendons (unit: mm).](image)

4.2. Effects of the External Prestressing Tendons under Optimized Layout

Under the effects of dead load and optimized external prestressing tendons, the deflection of the steel beam is large in the middle while small on both sides. The maximum deflection occurred in the middle, which was 625.68 mm. The minimum deflection occurred in the end, which was 416.60mm. Compared with the results calculated under only the effect of dead load, the deflection of the steel beam in the middle and end reduced by 16.10 mm and 12.60 mm, respectively. Compared with the results of the original external prestressing tendons, the two were enlarged by 23.3% and 58.1%, respectively. Thus, the effectiveness was significantly enhanced.

In terms of improving the stress of the general concrete beam, compared with the design layout, the reduction of the compressive stress at the bottom flange was smaller, with a range of 0.10~0.25 MPa. And the reduction of the tensile stress at the top flange was increased to 1.15~1.50 MPa. Besides, the tensile and compressive stresses of the concrete near the steel-concrete combining section were reduced. In general, the external prestressing tendons under the optimized layout is more conducive to the stress of the structure.

5. Tension Adjustment Plans for the External Prestressing Tendon

Due to long-term effects such as shrinkage and creep, the deflection of the traditional long-span prestressed concrete continuous rigid frame bridges will increase significantly in long-term service, which will affect its normal function. In order to explore the deformation of the hybrid beam rigid frame bridge under long-term effects, a finite element model was established for analysis. Since the tensile stress of the external prestressing tendons was only 30% (558 MPa) of the control stress when
completed, the external prestress can be re-tensioned to reduce the main span deflection when a large deflection occurs.

On the basis of considering the 10-year shrinkage and creep of concrete, the external prestressing tendons would be re-tensioned to 40% (744 MPa), 50% (930 MPa), 60% (1116 MPa), 70% (1302 MPa) and 75% (1395 MPa) of the control stress, respectively. The respective effects were calculated separately. The results are shown in table 2. Compared with the increase in deflection caused by the long-term effects, the reduction is smaller and increases linearly. The appropriate tension adjustment plans can be selected according to the actual deflection change.

**Table 2.** The deflection decreases under different tension control stresses in the steel beam (unit: mm).

| Tension control stress | Middle | End  |
|------------------------|--------|------|
| 30%                    | 16.1   | 12.6 |
| 40%                    | 20.2   | 15.8 |
| 50%                    | 25.6   | 19.9 |
| 60%                    | 31.0   | 24.1 |
| 70%                    | 36.3   | 28.3 |
| 75%                    | 39.1   | 30.4 |

6. Conclusions

(1) In this paper, the Anhaiwan Bridge in Quanzhou was taken as the background project. Through the finite element models, the role of external prestressing tendons in reducing the deflection of the steel beam and improving the mechanical performance of the concrete beams of the hybrid beam rigid frame bridge was carried out. Overall and local analysis was conducted separately.

(2) The effects of the external prestressing tendons were analyzed section by section through the finite element models. With the principle of improving the deflection of the steel beam and the stress of the concrete beams, the layout of the external prestress was optimized. It was figured out that if only the tendons parallel to the top flange and the diagonal tendons in the concrete beams are retained, the effects of the external prestressing tendons can be better.

(3) The deformation of the steel beam was calculated with the effects of long-term effects such as shrinkage and creep, considering the external prestressing tendons were re-tensioned. The effects of different re-tensioning adjustment plan on reducing the deflection of the steel beam was obtained for reference.

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