Design and Calculation of PC Composite Rigid Frame Bridge with Variable Section Steel Truss Webs

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Abstract. Steel truss web prestressed concrete composite bridge has many advantages, such as light weight, clear stress, beautiful structure, convenient construction, etc., but it is still in its infancy in China. Taking Shuinianbao bridge of Yanchong high speed as an example, this paper introduces the design method of PC composite rigid frame bridge with variable cross-section continuous steel truss web, and analyzes the static calculation of the whole bridge in combination with the code, so as to provide design reference for the construction and development of PC composite bridge with variable cross-section steel truss web. The analysis results show that: the calculation results obtained after modeling according to the design size meet the design requirements. Under the condition of ultimate bearing capacity, the top plate obtains a more uniform maximum resistance, and the arch curve makes the internal force of the bottom plate relatively small. Under the combination of short-term load effect, the main tensile stress of the inclined section appears at the position close to the support and the middle span section of the top plate. The main tensile stress of the steel truss web member is the most different under the unfavorable load combination, the maximum tensile stress is greater than the compressive stress, and the maximum tensile stress occurs at 1/4 of the mid-span.

Keywords: Composite bridge; Steel truss web; Variable section; Structural design; Static calculation.

1. Introduction
Steel truss web PC composite girder bridge is a new type of steel-concrete composite structure, which is rising in recent years. Its characteristic is that the box type web of the main girder of the bridge is replaced by truss steel structural members. The steel truss web members are fixed with the top and bottom plates of the main girder through specific node settings to achieve the transfer of force. After replacing the original concrete web with steel web, the steel truss web PC composite girder bridge has many advantages, such as light weight, clear stress, convenient construction, beautiful shape and so on. For example, Boulonnais viaduct in France adopts the combination of equal section steel truss web and concrete, which reduces the dead weight by 40% compared with the traditional bridge [1]. The new structure of steel truss web concrete composite beam is also adopted for the mu zhichuan viaduct in Japan, which not only optimizes the section rigidity of the beam, but also reduces the section thickness, makes the bridge light and beautiful, and integrates with the environment.

The mechanical properties of steel truss web bridge are studied at home and abroad. Kyushu University, Japan, carried out the scale model test of PBL joints used in the construction of steel truss web bridge, and carried out the nonlinear finite element analysis of the model [2]. Jung K., et al. carry out static load test on the reduced scale model of steel truss web prestressed concrete composite girder
bridge, and studied the bearing capacity, service performance and shear strength of joints of steel truss web girder [3]. Japanese scholars take zhi jinjian bridge as the background to carry out the static load test, and compare the measured deflection value with the theoretical deflection value [4]. Chen Yi-yan, et al. use the method of static load test to analyze the whole process of cracking and failure mode of steel truss web beam, and calculated the bearing capacity of steel truss web beam by the method of finite element and theory [5]. Wei Jian-gang, et al. conceive the truss web section based on the background of Ling-dou concrete arch bridge in Ningde. Through the comparative analysis of the finite element structure, it shows that the self weight of the steel truss web is 1/3 less than that of the original concrete web, and it also has certain economic advantages [6]. The first steel truss web concrete composite girder bridge designed and constructed in China is Nanjing Jiangshan bridge, which was completed in 2012 and arranged with two equal cross-section continuous beams [7]. Zhou Lingyu, et al. take a 4×60m constant section steel truss web concrete continuous beam bridge under construction as an example to analyze the mechanical effect of the joint [8].

In this paper, taking shui nian-bao overpass as an example (Figure 1), a PC composite rigid frame bridge with variable cross-section truss web, the design and static calculation process of the superstructure of the bridge are systematically introduced, which provides research background and design reference for the development of PC composite bridge with variable cross-section truss web in China.

![Figure 1. Shui nian-bao overpass.](image)

2. Engineering Survey
Shui nian-bao overpass is located at the main line of Yan-chong Expressway at K51 + 960. It is jointly designed by Hebei transportation planning and design institute and Southeast University architectural design and research institute Co., Ltd. The specific dimensions are shown in Figure 2. The upper structure is a variable section steel truss web prestressed concrete composite beam with a span of 30 + 40 + 30 m. The design load is highway class II. The main beam is a single box single chamber section with a full width of 5.5 m and a bottom width of 3.4m. The beam height at the end of the middle and side span of the main span is 2.0m, the height at the center line of the main pier is 3.5m, and the longitudinal bridge floor changes along the circular arc. In Figure 2, the four cross sections are drawn semi symmetrically. Section A-A is the section at the support, which is designed as concrete stiffened plate. Section B-B is at the starting point of the circular curve, which is composed of top plate, bottom plate and steel truss web member. With the change of the arc line, the steel truss web member is gradually lengthened until section C-C and section D-D is at the center of the pier, which is consolidated by the pier beam. The thickness of the pier wall is 120 cm, and a 100cm × 80cm manhole is set in the center to facilitate construction and maintenance.
Figure 2. Structural drawing of variable section steel truss web concrete continuous beam bridge(cm). C50 concrete is used for the top and bottom plates of the main beam, Q420qE grade steel is used for the steel truss web, and the node structure drawing of the connection between the steel truss web and the concrete top plate is shown in Figure 3. In the figure, the left side is the front view, and the right side is the side view. PBL connectors with high bearing capacity and rigidity are used, and anti sliding stud structure is configured. The size of the welding nail is $\Phi 19 \times 180$mm, and three rows of holes are set on the connecting steel plate for stirrup penetration, with an aperture of 60mm. The steel truss web section is $300\times 300$mm square, which is welded by 16mm thick steel plate, and the long-term anticorrosion of cold spraying zinc and modified fluorocarbon finish is adopted.

Figure 3. Structural drawing of steel truss web joint(mm).

The main beam is composed of internal and external prestressing, as shown in Figure 4. The internal prestressing tendon is mainly used to bear the first stage dead load and temporary construction load. Seven strands of high-strength and low relaxation steel strand complying with the provisions of GB/T 5224-2014 are used, with the standard strength of $f_{pk}=1860$MPa and the elastic modulus of $E_p=1.95 \times 10^5$Mpa. 10 $\Phi 15.2$ steel strand is used for the top and bottom plates, and the control stress of tension under the anchor is 1395MPa. External prestressing is mainly used to resist the second stage dead load and live load. The filled epoxy coated steel strand complying with the provisions of GB/T 21073-2007 is adopted, with the standard strength of $f_{pk}=1800$MPa and elastic modulus of $E_p=1.95 \times 10^5$Mpa. After the internal prestress is tensioned, the external prestress is tensioned, and the control stress is 1209MPa. In order to prevent the vibration frequency of the free section of the cable body close to the overall vibration frequency, the damping device is set at the appropriate position (Fig. 5).
3. Calculation and Analysis

In this paper, Dr. bridge v4.0 is used for modeling calculation and analysis. The longitudinal calculation is mainly based on the bar system theory. The top plate, bottom plate and truss web of the box girder are set as plane elements respectively. The static situation of the structure after the completion of the bridge is analyzed and checked. The whole bridge is divided into 341 units, and the structure is discrete as shown in Figure 6. The load is highway class II, the designed bridge temperature is 10 ℃, the system temperature is 30 ℃, the system temperature is 40 ℃, the wind speed is 32.5m/s, and the uneven settlement of 10 mm main pier foundation and 5 mm abutment foundation is considered. The seismic action is 7 degree area, and the design basic acceleration is 0.15g.

3.1. Ultimate State Analysis of Box Girder Bearing Capacity

In Figure 7, the maximum and minimum resistance of top plate and bottom plate and the internal force corresponding to the resistance are given symmetrically, and the bending moment values of representative points are marked. It can be seen from the figure that the combined value of load effect in all regions in operation stage is less than the design value of bearing capacity of main girder. The maximum resistance of the roof and the corresponding internal force value are relatively uniform, and the mean value of the internal force corresponding to the resistance accounts for 47.8% of the mean value of the maximum resistance. The internal force corresponding to the resistance in the main span of the bottom slab is only 1606kN·m, accounting for only 7.0% of the maximum resistance in the span. The minimum resistance of roof is close to the maximum resistance, while the corresponding internal force is relatively small. Due to the advantage of arch curve, the minimum resistance value of the bottom slab is relatively large. The side span and the middle span reach 27869kN·m and 27556kN·m respectively. The internal force corresponding to the minimum resistance is larger than that corresponding to the maximum resistance, and the internal force corresponding to the minimum resistance is smaller than that corresponding to the minimum resistance. In conclusion, under the condition of ultimate bending capacity, the internal force corresponding to the resistance is about half
of the resistance value, which meets the requirements of bending capacity specification.

![Figure 7. Resistance and internal force diagram corresponding to resistance(kN·m).](image)

3.2. Crack Resistance Analysis of Box Girder in Serviceability Limit State

According to the code [9], for prestressed concrete class A, the crack resistance of the normal section should be checked. Figure 8 shows the calculation results of the minimum normal stress of the normal section under the combination of short-term load effect and long-term load effect. In this figure, tensile stress appears in some sections under short-term load effect combination, for example, the location of pier top plate is 0.14MPa, and the maximum size of mid span bottom plate is 0.82 MPa. Under the combination of short-term and medium-term effects of the code, it is required that the difference between the normal tensile stress of edge concrete and the pre compression stress produced by prestress shall not exceed 0.7 times of the standard value of concrete tensile strength, that is, $\sigma_{st} - \sigma_{pc} \leq 0.7f_{tk} = 0.7 \times 2.65 = 1.86MPa$, which can be seen that the code meets the requirements. In Figure 8, under the long-term load effect combination of box girder, the calculated value of minimum pressure is 2.50MPa, without tensile stress, meeting the requirements of the code.

![Figure 8. Minimum positive stress diagram of section under short-term and long-term load effect combination(MPa).](image)

In addition, figure 9 shows the calculation results of the main tensile stress of the concrete with inclined section of the main beam top plate and bottom plate under the short-term load effect combination. In the figure, there is a large tensile stress near the support of the top plate and at the section of the middle span, which are 1.04 and 1.06 MPa respectively; the main tensile stress of the bottom plate at the side span is small, and the large tensile stress at the section of the middle span is 1.04MPa. In the code, for the partial prestressed concrete class A, the main tensile stress produced by the prefabricated members under the short-term effect combination should not exceed 0.7 times of the standard resistance strength of the concrete, and that of the cast-in-place members should not exceed 0.5 times. Therefore, it can be concluded that $\sigma_{tp} \leq 0.5f_{tk} = 0.5 \times 2.65 = 1.33MPa$. It can be seen that the main tensile stress does not exceed the value required by the code.
3.3. Stress Analysis of Prestressed Concrete Members in Permanent Condition

Figure 10 shows the calculation results of the maximum positive pressure stress and the main pressure stress under the combination of the standard value of load effect. In order to prevent the concrete from being damaged by compression, the specification specifies the prestressed concrete in the use stage, and requires that the maximum compressive stress of the concrete in the normal section of the concrete flexural member should not exceed 0.5 times of the standard compressive strength. In the figure, the maximum positive pressure stress is large in the upper section of the plate, the maximum value of the top plate is 15.22MPa, the maximum value of the bottom plate is 14.76MPa, all of which do not exceed the specified value of $0.5f_{ck} = 16.2$MPa. The figure also shows the maximum main pressure stress of the main beam under the load standard value combination of the normal service limit state. The maximum main pressure stress of the side span of the top plate increases slightly from the support to the pier, and the middle span is relatively uniform, with the maximum value of 14.89MPa; the maximum main pressure stress of the middle span of the bottom plate is 15.15MPa, which is less than $0.6f_{ck}=19.44$MPa required in the specification.

3.4. Stress Analysis of Steel Truss Web

The calculation model calculates and analyzes the possible maximum tensile and compressive stress of steel truss web members, as shown in Figure 11. The figure shows the maximum stress value of 22 side span and 15 middle span steel truss web members under the most unfavorable load combination, in which the maximum tensile stress (26) is greater than the compressive stress (11). In the middle of the side span, the maximum axial stress of the steel truss web member gradually decreases from the support to the pier, and the maximum stress at the support is 90MPa; the maximum stress at the middle span pier and the mid span is smaller, while the maximum stress at 1/4 is larger, the maximum stress is
110MPa, which is far less than the bending stress of the steel Q420qE.

**Figure 11.** Maximum stress diagram of steel truss web member(MPa).

### 4. Conclusions

Taking Shui nian-bao overpass as an example, this paper systematically introduces the design dimension and connection structure of PC composite rigid frame bridge with variable cross-section truss web, and makes static calculation and analysis, all of which meet the requirements of the code. The main conclusions are as follows:

1. In the condition of ultimate bearing capacity, the maximum resistance of the roof is relatively uniform, and the internal force corresponding to the resistance is about half of the resistance value. Due to the advantage of arch curve, the internal force corresponding to the resistance is relatively small.

2. Under the combination of short-term load effect, there are few sections with tensile stress under the action of prestress, and there is no tensile stress under the combination of long-term load effect. Under the combination of short-term load effect, the main tensile stress of inclined section appears near the support and the mid span section of the roof.

3. Under the combination of load effect standard values, the upper section of the slab will have a large positive pressure stress. Under the load standard value combination of the serviceability limit state, the maximum main pressure stress of the side span of the roof increases slightly from the support to the pier, and the middle span is relatively uniform.

4. Under different most unfavorable load combinations, the maximum tensile stress is greater than the compressive stress. The maximum stress of the side span is gradually reduced from the support to the pier, and the maximum tensile stress of the middle span is 1/4 of the value.

5. Due to its advantages of light weight, reasonable structural stress and convenient construction, steel truss web bridge can be widely used in the construction of medium span bridges.

### References

[1] Kai-li Chen. Brief introduction of Boulonnais viaduct in France. Foreign Bridges. 01(1999)15-17. (in chinese)

[2] Kwang-Hoe Jung JJKJ. Development and Evaluation of New Connection Systems for Hybrid Truss Bridge. Journal of Advanced Concrete Technology. 11(2013) 61-79.

[3] Jung K, Yi J, Kim JJ. Structural safety and serviceability evaluations of prestressed concrete hybrid bridge girders with corrugated or steel truss web members. Eng Struct. 32(2010) 3866-3878.

[4] Ying-ying Zhang, Jian-dong Zhang, Xue-hong Li, et al. Study on the basic mechanical properties of steel truss web prestressed concrete composite box girder bridge. Highway. 11(2012) 55-59. (in chinese)

[5] Yiyan Chen, Jucan Dong, Zhaojie Tong, et al. Flexural behavior of composite box girders with corrugated steel webs and trusses. Eng Struct. 209(2020)110275.

[6] JiangGang Wei, Tingmin Mou, Feng Miao, et al. Trial design of a new type of composite box arch bridge with steel web member and concrete. Traffic science and Engineering. 02 (2009)40-45. (in chinese)
[7] Duo Liu, Jiandong Zhang, Weiguo Yan. Design and construction of Jiangshan bridge around Nanjing highway. Highway. 58(2013) 80-83. (in chinese)

[8] Lingyu Zhou, Xianxing Xue, Longxiang Li, et al. Multi-scale analysis of steel truss continuous box girder bridge considering joint stiffness. Journal of Railway Science and Engineering. 15(2018) 2851-2860.

[9] JTG 3362-2018, Code for design of highway reinforced concrete and prestressed concrete bridges and culverts. Ministry of Communications of the People's Republic of China, Beijing, 2018.