Analysis of Parameter Sensitivity of Construction Control of Multi Span PC Continuous Beam Bridge with Corrugated Steel Webs

Dianyuan Liu 1,2, Tiedong Qi 1,2
1Research Institute of Highway, Ministry of Transport, Beijing 100088, China;
2China Road Transport Inspection & Certification Hi-tech Co.Ltd, Beijing 100088, China
*Corresponding author’s e-mail: dianyuan.liu@ctvic.cn

Abstract: In order to study the sensitivity of construction control of multi span PC continuous beam bridge with corrugated steel webs, taking the main bridge of Yesheng Yellow River Highway Bridge in Ningxia as an example, the space finite element analysis software is used to simulate the bridge and calculate the construction control. In the process, different values of the main parameters of the structure affect the degree of the linear and internal stress of the bridge. The calculation results show that the effects of shrinkage and creep of concrete roof and floor, segmental weight and temperature gradient on the deformation and stress of the main beam are obvious; the elastic modulus of the concrete has a certain degree of influence on the deformation and stress of the main beam, and the influence of the prestressing parameters is smaller. Therefore, in the process of construction control, the influence of shrinkage and creep of the concrete roof and floor shall be considered, the weight of the main beam shall be strictly controlled, and the effect of the measurement time and the temperature gradient effect shall be taken into account in the linear monitoring.

1. Preface
Since the emergence of prestressed concrete bridges in the 1930s, modern bridges have made great progress and the bridge spanning capacity has reached a whole new level. But for prestressed concrete box girder, due to the need to arrange steel bars and prestressing bars in the web turning, the thickness of the web is large, and the area of the web generally accounts for about 25% to 35% of the total cross-sectional area. In order to reduce the thickness of the web, the idea of using flat steel webs instead of the concrete webs of traditional box beams was first proposed in France. But the deformation caused by the shrinkage and creep of the concrete on the upper and lower flanges is constrained by the steel webs, so that the prestress of the upper and lower flanges tends to be transferred to the steel webs, which greatly reduces the prestress use efficiency. In order to solve the cross-section prestress loss caused by the restraint of the steel webs, the French company Campenon Bernard proposed the idea of replacing the flat steel web with a corrugated steel web in 1975. Through a large number of finite element analysis and model tests and researches, and the world's first corrugated steel web prestressed composite box girder bridge-Cognac Bridge[1] was completed in France in 1986.

Bridge construction control is a complex and systematic project and various factors in the construction process may have important impacts on the results of construction control. The systematic researches on the influence of the key parameters of the structure on the structural...
mechanical behavior, the subsequent determination of reasonable construction control schemes, the guidance of selecting key manufacturing parameters for manufacturing and installation sections, and parameter identification and error evaluation during construction are of great significance[2]. The main purpose of parameter sensitivity analysis is to determine the key control parameters during construction, to provide the basis for the formulation of the control plan, to determine the influence of the deviation of the key parameters on the control results, to provide a scientific basis for the identification and error correction of the construction control parameters, and finally, to ensure the safety of the structure during construction and the smoothness of the line after the completeness of bridge[3].

There are many calculations and related studies on the sensitivity analysis of construction control parameters of PC continuous beam bridges and continuous rigid frame bridges in China[4]-[6], but examples and literatures which discussing the sensitivity analysis of construction control parameters of continuous beam bridges with corrugated steel webs are few. An Yongri et al. had previously discussed the influence of the stiffness of the pier of PC composite box girder pylon cable-stayed bridge with corrugated steel webs on the internal stress of the main girder and the influence of variation of tower height on the internal stress and the cable stay of the main girder.[7] Zhang Xingzhi once carried out a force analysis and research on the construction process of PC composite continuous beam bridge with corrugated steel web[8], and made an analysis of the influence of the external prestressing system on the stress of the bridge structure. However, none of the control parameters during construction were analyzed.

Taking the main bridge of the Yesheng Yellow River Bridge in Ningxia as an example, the sensitivity analysis of the structural response under various design parameters is performed in this paper to determine the sensitivity and the key parameters that affect the construction control of a multi-span continuous beam bridge with corrugated steel webs so as to provide some references for construction controls.

2. Project Overview
The upper structure of the main bridge of the Yesheng Yellow River Bridge in Ningxia is a seven-span corrugated steel web prestressed concrete box girder with a main span of 120m, and the span is $64 \times 5 \times 120 + 64 = 728m$. The overall layout is shown in Figure 1. The single main beam is in the form of a single box and single room inclined web, the standard cross-sectional view is shown in Figure 2. The single box beam has a top plate width of 15.25m and a bottom plate width of 4.8m ~ 6.39m. The mid-span beam is 3.7m high and the height of root beam is 7.5m with the transition of 1.6 times parabola. The ratio of the height to the span of the mid-span beam is 1 / 32.4, and the ratio of the beam height to the span of the mid-pier fulcrum is 1/16. The thickness of the roof is 30cm, the thickness of the flange is 18cm ~ 70cm, the length of edge plate cantilever is 3.8m; the thickness of mid-slab is 30cm, and the root bottom plate is 100cm thick with the transition of 1.6 times parabola. The wave length of the steel web of the upper structure is 1.60m, the wave height is 0.22m, the horizontal panel width is 0.43m, and the horizontal folding angle is 30.7°. The bending radius is 15t (t is the thickness of the corrugated steel web). The thickness models of the corrugated steel web include 12mm, 14mm, 16mm, 18mm, 20mm, and 25mm.

The main beam sections are divided into 18 types, the 0, 1, and 2 beam sections are the cast-in-situ sections of the middle pier roof supports, the 3 to 14 beam sections are the hanging cantilever cast sections, and the 15a and 16 beam sections are the side span supports.15b is the mid-span helong section. For the construction method of the main beam, the 0-beam section, the 1-beam section, the 2-beam section, and the side-span 15a and 16-beam sections are cast in place on the support, and the mid-span helong beam section is cast in the place on the gondola, and the remaining blocks adopt the hanging-cantilever cantilever construction stage with the main beam and the bridge pier of temporary consolidation treatment.
3. Computational Models

The calculation uses the bridge general finite element program Midas / Civil to establish a three-dimensional finite element model of the main bridge of Yesheng Yellow River Bridge. The main beam is simulated by a three-dimensional beam element with a total of 204 units and 205 nodes. The steel web and the upper and lower concrete flange plates are considered to be consolidated during the calculation and they work together without relative sliding or shear connection failure. During the model calculation, a flat steel web is used instead of a corrugated steel web, and the fold effect of the corrugated steel web is considered to be equivalent to the stiffness passed by the program. What's more, the boundary conditions after completion of the bridge are all sliding bearings except that Pier 9 is a fixed bearing.

The dead load of the first phase is taken from the structure's own weight and calculated automatically by the program according to the actual cross-sectional dimensions of the bridge members. The dead load of the second phase is 83.78kN/m. The vehicle load adopts Highway-I level, and is calculated according to the three lanes, taking into account the lateral reduction of lanes and the effects of eccentric load. The calculation of shrinkage and creep adopts the specification model of "Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" (JTG D62-2004), and the strength development model is based on CEB-FIP. The effect of temperature is considered to increase the overall temperature by 25.2 ℃ and decrease the overall temperature by -26.7 ℃. The finite element calculation model is shown in Figure 3.

4. Parameter Sensitivity Analysis

Considering the actual situation of the construction process of the main bridge of the Yesheng Yellow River Bridge, a sensitivity analysis is performed in this paper on the main parameters for the purpose of studying the effects of changes in the main parameters of the structure on the mechanical behavior of the bridge structure. The main parameters analyzed include the elastic modulus, the weight of the
beam section, the shrinkage and creep of concrete, temperature gradient effects, and prestress parameters\cite{9}-\cite{11}.

The influence of the main parameter changes on the mechanical behavior of the structure mainly includes the linear and internal stress of the main beam. In the parameter sensitivity analysis of the structure, a single-variable method is adopted, that is, the values of rest of the parameters are based on the baseline state.

4.1. Modulus of Elasticity

When analyzing a PC composite beam bridge with corrugated steel webs, it is considered that the bending moment and axial force of the structure are borne by the concrete roof and floor, and the shear force is borne by the corrugated steel webs. Based on this statement, the sensitivity of the elastic modulus only considers the elastic modulus of the concrete. According to the previous construction experience of continuous beam bridges and continuous rigid frame bridges, in general, the measured elastic modulus of concrete of the bridge is higher than the recommended value of the code, usually up to 1.1 times the recommended value of the code\cite{3}\cite{4}. The box girder concrete of the Main Bridge of Yesheng Yellow River Bridge uses C55 concrete, and the recommended value of the elastic modulus is $3.55 \times 10^4$ MPa. Calculating the internal stress and deformation of the main beam in the maximum cantilever state when the elastic modulus of concrete is calculated to be 0.9, 1.0, and 1.1 times the recommended value, The calculation results of the bending combined stress at the root of block 0 of the main beam are shown in Table 1 (the negative value of the stress in the table is compressive stress and the positive value is tensile stress). The deformation of the main beam is shown in Figures 4 and 5.

| Elastic Modulus | Upper edge | Lower edge |
|-----------------|------------|------------|
| 0.9E            | -8.40      | -7.32      |
| 1.0E            | -8.42      | -7.31      |
| 1.1E            | -8.44      | -7.30      |

Table 1. Bending combined stress of main beam of block 0 with different values of elastic modulus

![Figure 4. Deformation of the main beam with different values of elastic modulus](image)

From Table 1, it can be seen that the effect of the increase and decrease of the elastic modulus of concrete on the stress of the main beam is almost zero, therefore its effect on the stress can be ignored. From Figure 4, it can be seen that when the elastic modulus changes by 10\%, the effect on the deformation of the main beam is relatively small and the maximum change in deformation is only 1.53mm.
4.2. Beam Section Weight

During the construction process, the weight of the beam section will often change due to factors such as concrete over-squares, formwork deformation, and changes in the concrete bulk density. The concrete bulk density of the main bridge of the Yesheng Yellow River Bridge is calculated at 26kN/m³, and the concrete bulk density is calculated to be 0.9, 1.0, and 1.1 times the recommended values and the internal stress and deformation of the main beam is calculated at the maximum cantilever state. The calculation result of the bending combined at the root of block 0 of the main beam is shown in Table 2 (the negative stress value in the table is compressive stress, and the positive value is tensile stress). The deformation of the main beam is shown in Figures 5 and 6.

| Elastic Modulus | Stress / MPa |
|-----------------|--------------|
|                 | Upper edge   | Lower edge   |
| 0.9γ            | -9.23        | -6.27        |
| 1.0γ            | -8.42        | -7.31        |
| 1.1γ            | -7.62        | -8.35        |

Table 2. Bending combined stress of the main beam of block 0 with different values of bulk density

Figure 5. Deformation of the main girder with different values of bulk density during the bridge completion stage

Figure 6. Deformation of the main beam with different values of bulk density at the maximum cantilever stage

It can be known from Table 2 that when the weight of the main beam section changes, the influence of the main beam stress is more obvious. When the weight of the beam section is reduced by
10%, the compressive stress at the upper edge of the root of No. 0 block of the main beam increases by 0.81 MPa, and the compressive stress at the lower edge decreases 1.04 MPa; when the weight of the beam section is increased by 10%, the compressive stress at the upper edge of the root of No. 0 block of the main beam decreases by 0.80 MPa, and the compressive stress at the lower edge increases by 1.04 MPa; as shown in Figure 5, when the weight of the beam section changes by 10%, the maximum deformation of the main beam in the state of maximum cantilever is 7mm. Therefore, during the construction control process, attention should be paid to the control of the weight of the beam section of main beam, and the concrete bulk density should be collected in time to correct the calculation model in real time.

It can be known from Figures 5 and 6 that when the weight of the beam section changes by 10%, the maximum linear difference of the main beam in the bridge stage is 9.93mm, and the maximum linear difference of the main beam in the cantilever stage is 6.95mm. The weight change of the beam section of the main beam has a sensitive influence on the line shape. In the construction process, attention should be paid to the collection of the bulk weight data of the main beam, and the weight of the beam section should be controlled.

4.3. Shrinkage and Creep Effect of Concrete Roof and Floor

The roof and floor of the box girder bridge with corrugated steel web are made of concrete material, and the web is made of steel. Concrete will shrink and creep, but steel will not. Its shrinkage and creep effect is different from conventional prestressed concrete continuous beam bridges. Therefore, it is necessary to study the shrinkage and creep effect of PC composite beam bridge with corrugated steel web. This paper studies the effects of concrete shrinkage and creep on the internal stress and deformation of PC composite beam bridge with corrugated steel web in three cases. 1) No considering Shrinkage and creep effects; 2) Only considering shrinkage and creep effects during construction process; 3) Considering shrinkage and creep effects after 10 years of bridge construction. The calculation results of the combined bending stress of the roof and floor of the main beam are shown in Figures 8 and 9 (Figures (The negative stress value is compressive stress and the positive value is tensile stress). The deformation of the main beam is shown in Table 3.

![Figure 7: Effect of shrinkage and creep on the stress of the roof of main beam](image-url)
Regardless of shrinkage and creep
Only considering the shrinkage and creep during construction
Considering the 10-year shrinkage and creep of the completed bridge

![Graph showing stress and mileage relationship](image)

Figure 8. Effect of shrinkage and creep on the stress of the floor of the main beam

### Table 3. Effect of shrinkage and creep on deformation of main beam

| Shrinkage creep                      | Vertical deformation | Beam end longitudinal displacement |
|--------------------------------------|----------------------|------------------------------------|
| No considering                       | 26.14                | 43.17                              |
| Considering only the construction process | 35.31                | 79.52                              |
| Considering bridge for 10 years      | 37.90                | 164.32                             |

It can be seen from Figures 7 and 8 that the effect of shrinkage and creep on the stress of the concrete floor is more significant than that of the roof. Considering the 10-year comparison of the bridge without considering shrinkage and creep, the maximum difference in roof stress is 1.50MPa, and the maximum difference in roof stress is 4.30MPa. The influence of the shrinkage and creep effect on the concrete roof and floor of the main beam cannot be ignored.

It can be seen from Table 3 that the shrinkage and creep effect of the main beam has a significant effect on the vertical and longitudinal deformation of the main beam during the construction stage. The subsequent shrinkage and creep mainly affects the longitudinal deformation of the main beam and has a large impact on the longitudinal displacement of the main beam which is reached 84.8mm. Therefore, in the control of linear of the main beam during the construction phase, the impact of the shrinkage and creep of the concrete roof and floor during the construction process should be considered when setting the pre-arch value. Due to the obvious influence of later shrinkage and creep effect on the longitudinal displacement of the main beam, post-shrinkage and creep effect should be taken into considered to pre-deflect the support when installing the support of multi-span PC composite box girder bridge with corrugated steel webs.

### 4.4. Temperature Gradient Effect

As for the temperature load effect, the sunshine temperature difference load and seasonal temperature difference load are mainly considered during construction control. For the seasonal temperature difference has no obvious effect on the structure while the sunshine temperature difference has a greater influence on the linear during the construction of the main beam, especially at the maximum cantilever stage, only the sunlight temperature difference load is analyzed when analyzing the effect of temperature load on the bridge construction control. According to two modes in the design specification, that is, rising 14°C and cooling 7°C of roof of the temperature gradient load, the internal stress and deformation of the main bridge of the Yesheng Yellow River Bridge at the maximum cantilever state phase is analyzed. The specific analysis results are as follows.
### Table 4. Effect of temperature gradient change on the deformation of main beam at the maximum cantilever stage

| Temperature gradient | Cantilever end vertical displacement /mm | Rate of change of displacement /mm•℃⁻¹ |
|----------------------|----------------------------------------|---------------------------------------|
| Rising 14 ℃         | -14.89                                 | -1.06                                 |
| Cooling 7 ℃         | 7.45                                   | 1.06                                  |

Figure 9. Effect of temperature gradient change on the stress of the main beam at the maximum cantilever stage

From Table 4, it can be seen that the temperature gradient load has a significant effect on the deformation of the main beam in the maximum cantilever state. While the temperature difference between the roof and floor changes by 1 °C, the line shape of the main beam changes by 1.06 mm. As can be seen from Figure 9, for the stress of the main beam in the maximum cantilever state, the stress change of roof is more obvious than that of the floor under the same temperature gradient load, and the stress change at the root of the cantilever end is the largest.

During the construction control, especially the line shape control, it is necessary to monitor the phase alignment of the main beam. When monitoring, the measurement time is generally controlled at night or on a cloudy day to avoid the influence of the temperature gradient load caused by the temperature difference on the main beam alignment. When the actual operation on site is not allowed, the temperature field of the main beam must be monitored, and the temperature effect analysis should be performed according to the distribution of the measured temperature field to eliminate the effect of temperature gradient load on the line shape of the main beam.

### 4.5. Prestressing parameters

For the longitudinal prestress of the corrugated steel web-PC composite box girder, a system combining internal prestress and external prestress is generally used. All the prestresses of the box girder cantilever construction and the box girder when closing are used internal prestress to resist the first-phase dead load and temporary load during construction, while the external prestressing of the box girder in the continuous state is used to resist the second-phase dead load and live load. Therefore, the analysis of the sensitivity of the prestress parameters of the PC composite box girder bridge with corrugated steel web needs to take into account the internal prestress system and external prestress system at the same time. The value of pipeline friction coefficient of internal prestress of YeSheng Yellow River Bridge is 0.17, the pipeline deviation coefficient k is 0.0015, and the anchorage retraction value is 6mm. The internal prestress parameters are analyzed and calculated according to a 10% change. The calculation results show that the overall effect of changes in prestress parameters on
the alignment and stress of the main beam is small, the maximum impact on the alignment does not exceed 1mm while the maximum impact on the stress does not exceed 0.10MPa.

In addition, for the external prestress system, it is not affected by pipeline friction but related to the angle between the anchoring point of the prestressed beam and the horizontal axis of the bridge. As long as the position of the steering block is accurately positioned during construction, the control of the included angle is relatively easy to achieve, thus no specific analysis is done here.

5. Conclusion

In this paper, the main bridge of the Ningxia Yesheng Yellow River Bridge is taken as an engineering example to calculate the influence of changes in the values of the main parameters on the alignment and internal stress during construction. The calculation and analysis results show that the shrinkage and creep of concrete roof and floor, weight of beam section and temperature gradient effect have more obvious effects on the deformation and stress of the main beam; the elastic modulus of concrete has a certain degree of influence on the deformation and stress of the main beam, and the prestress parameters have a small effect.

(1) In the process of construction control, the time-varying effect of the concrete roof and floor should be considered, and the impact of shrinkage and creep should be taken into account. During the calculation, the division of the construction phase is strictly simulated according to the actual construction progress, and the construction unit shall implement the established construction as much as possible.

(2) The weight of beam section of the main beam should be strictly controlled during the construction process, and the real-time correction of the weight of the beam section should be considered in the calculation.

(3) The measurement time requirements must be considered during linear monitoring to avoid the effects of temperature gradient loads as much as possible. If the field operation is not allowed, the temperature field of the main beam must be monitored and the effects of temperature gradient effects must be taken into account.

Sensitivity analysis is an indispensable part of construction control work. The results of the analysis and research in this paper have been directly applied to the construction control of the Yesheng Yellow River Bridge in Ningxia. It has high practical value and can also provide certain references for construction controls of similar bridge types.

References
[1] Shuqin Li, Shui Wan, Fei Le. Structural Analysis and Example of PC Composite Box Girder Bridge with Corrugated Steel Web [M]. Beijing: People's Communications Press, 2015.
[2] Xuefei Shi. Estimation of Structural Parameters and Construction Control System of Cable-stayed Bridge [D]. Shanghai: Tongji University Doctoral Dissertation, 1999.
[3] Songsong Ma, Congcong Yu, Bo Geng. Analysis for Sensitivity of Control Parameters in Construction of PC Continuous Steel Structure Bridges [J]. Technology of Highway and Transport 2013 (4): 93-100.
[4] Xianhong Ma, Yi Yu. Analysis of Parameter Sensitivity of Construction control of High-Rise Pier and Long span Continuous Rigid-Frame Bridge [J]. Bridge Construction, 2012 (3): 57-62.
[5] Longsheng Bao, Chengzhong Xiao, Ling Yu, Dongwen Song. The Research of the Sensibility Analysis of Design Parameters in Long-Span Concrete Continuous Girder Bridge Construction Monitoring [J]. Journal of Shenyang Jianzhu University (Natural Science). 2012 (06): 1068-1073.
[6] Musheng Xiang, Shibiao Zhang, Kaiyin Zhang, Diandong Shen, Chengwu Shen. Control Technique for Construction of Long Span Prestressed Concrete Bridge [J]. China Journal of Highway and Transport; 2002 (4): 38-42.
[7] Yongri An, Song Zeng, Fang Wang, Chenglin Lü. Parameter Analysis for Parameters of Waveform Steel Web-PC Combined Box Girder Short Tower Cable-stayed Bridges [J]. Technology of
[8] Xingzhi Zhang. Construction of PC Composite Continuous Box Girder Bridge with Corrugated Steel Webs and Analysis of Prestress Parameters [D]. Chengdu: Southwest Jiaotong University, 2009.

[9] Juntao Qiang, Chen Yao, Feng Zhang, Xiaoyan Liu. Study of Temperature Effect on the Composed Bridge with Corrugated Steel Webs [J]. Highway 2016 (3): 54-57.

[10] Mingmin Tang. Study on Mechanical Properties in Cantilever-construction and Temperature Field Effects of Prestressed Concrete Composite Box-girder Bridge with Corrugated Steel Webs [D]. Nanjing: Southeast University, 2013.

[11] Yanhai Yang. Creep Behavior of Box Girder with Corrugated Steel Webs [D]. Beijing: Beijing Jiaotong University, 2013.