Temperature Effect on Main Girder of Strengthened Dongming Huanghe River Highway Bridge in Service

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Abstract. The main girder of Dongming Huanghe River Highway Bridge was the first prestressed concrete (PC) continuous box girder bridge strengthened by a cable-stayed system in China. In order to study the temperature effect of the main girder structure of Dongming Huanghe River Highway Bridge after reinforcement, based on the measured data of middle span deflection, key section strain and typical crack width, the curve equations of strain and temperature of main girder were obtained by the regression analysis method. The results show that the annual strain value of main girder changed with the acquisition time in a sinusoidal function, and was linearly related to the temperature. The variation of mid-span deflection decreased gradually from side span to middle span, and varied dynamically with temperature in the whole girder, which also has obvious correlation with temperature. The crack width fluctuated up and down in a certain numerical range, which belonged to respiratory cracks and had equally correlation with temperature.

1. Introduction

PC continuous box-girder bridge with high flexural and torsional stiffness, comfortable driving, smooth and beautiful, low maintenance costs, convenient construction, took the first place at the triennial palace examination [1]. From the survey and maintenance of bridges over the past 20 years in China, long span PC continuous box-girder bridge generally appeared deflection in different degrees. The cracks was a complication of long span PC box girder bridge deflection. Two diseases were evolving over time and influencing each other, which leaded to a reduction in the bearing capacity of the bridges, seriously affected the normal operation, even caused the collapse. Worldwide, long span PC continuous box-girder bridge also had typical diseases. For example, the Koror-Babeldaob (KB) Bridge in the Republic of Palau had collapsed after reinforcement [2]. According to the incomplete statistics of literature [3], dozens of PC continuous box-girder bridge of Jiangsu and Zhejiang provinces in China need to be strengthened or removed ahead of time.

The main causes of long span PC continuous box-girder bridge diseases included: prestress loss; concrete shrinkage and creep; box-girder cracking; unreasonable geometric design parameters; poor construction methods and construction quality, et.. Through the traditional strengthening methods, such as expanding the section size of box girder, pasting steel plate or carbon fiber, adding external tendons had been obtained in the application of real bridge [4-8]. However, there were obvious
shortcomings in the reconstruction of bridges with large span and serious deflection. The reasons mainly included two aspects: firstly, most of the reinforcement methods were passive and could not actively raise the cross section height of main girder; secondly, adding external tendons were limited to improve the web shear capacity and raise the cross section height. Cable-stayed system (SCS) reinforcement was a good method to change the force system by adding bridge tower and cable to provide vertical support to the main girder. During Puttesund Bridge reconstruction in Norway, the maximum allowable deflection in the top of steel tower and the tension control measures of each stage were adopted. The maximum allowable deflection was controlled within the range of -1cm~1cm, and the cable force was controlled according to the tensioning scheme. When the limit value was reached, the tension was stopped. When the tension was finished, the lifting height of middle span was 28cm, and added 7cm after one month. In order to study the influence of the temperature on main girder after the reinforcement by a cable-stayed system, this paper analyzed the middle span deflection of main girder, the strain of the key section, and the change of typical crack width collected by the real bridge.

2. Project background

The main girder of Dongming Huanghe River Highway Bridge was from the original PC continuous rigid frame-continuous girder combination structure to the existing low tower cable-stayed system structure, and is a variable section box girder, nine holes and one couplet. The span assembly is (75 + 7×120 + 75) m. Among them, No. 61~64 pier were consolidated with main girder, and support systems were set for other piers. Applying continuous rigid frame-continuous girder combination system to reduce the additional internal force of the structure formed by system transformation, enhancing structural integrity, improving the seismic performance of the whole bridge. This bridge was the first long-span PC continuous box girder bridge strengthened by a SCS, while we could learn from experience was not much [9]. Compared with other strengthening methods [10-11], the construction procedure of SCS strengthening was more complicated, and the local stress concentration of main girder was more prominent due to tensioning construction. Tensioning stay cables may make the tensile stress of main girder too large, caused the cracking and the sudden loss of stiffness of main girder, eventually led to the collapse. By establishing a reasonable, safe and efficient tensioning scheme and accurately controlling the cable force, the deformation and stress change of key measuring points cloud be ensured within the control index. Figure 1 was the main bridge of Dongming Huanghe River Highway Bridge before and after SCS reinforcement. In 2019, the total number of bridge vehicles was about 4.63 million, and vehicles were concentrated in the second and third lanes. Vehicles with speed over 100km/h accounted for 25.85% of the vehicles passing the bridge, mainly concentrated in January and February. Vehicles with weight over 100t accounted for 2.30% of the vehicles passing the bridge, mainly concentrated in July, August and September.

Figure 1. The Dongming Huanghe River Highway Bridge before and after reinforcement.
3. Long-term monitoring points layout

3.1. Stress and deflection test section layout
The monitoring of main girder was in normal operation from January 2019 to December 2019, and the sampling frequency of data was once an hour. The strain control section of main girder was selected as one middle section and two top sections of pier, and five test sections were arranged in the main girder. Four sensors were arranged on each testing section, and two were placed on the upper and lower margin. One temperature sensor was arranged corresponding to each measuring point to monitor the structure temperature and compensated the strain at the same time. The middle position of each span was selected as the control section of the main girder deflection, and the base point was arranged at the No. 58 pier. The deflection of main girder and pier abutment were tested by static force level. The deflection of each section was calculated by the accumulation of deflection value. A total of three span test sections, deflection measuring points and box girder stress section layout are shown in figure 2.

Figure 2. Layout of stress and alignment monitoring section.

3.2. Stress and deflection test section layout
After the strengthening main bridge was completed, we selected typical cracks to observe based on the structural profile. One crack observation point was arranged in the web of each span, and the crack monitoring points were selected nine typical cracks in the main girder. Long-term monitoring was carried out at the downstream web which was 92m away from No. 59 pier, downstream web which was 82m away from No. 62, upstream web which was 93m away from No. 65, downstream web which was 88m away from No. 63, upstream web which was 36m away from No. 62, upstream web which was 94m away from No. 61, downstream web which was 47m away from No. 60, downstream web which was 54m away from No. 58, and upstream web which was 34m away from No. 59.

4. Analysis of long-term monitoring results

4.1. Stress variation law and regression analysis result
Figure 3 (a)-(e) showed the relationship lines between stress, temperature and annual testing time on the upstream bottom and top slab of pier top sections in the lower side of No. 59 span, the upstream bottom and top slab of No. 59 mid-span sections, the downstream bottom slab of pier top sections in the higher side of No. 60 span. Compared with the bottom slab of main girder, the temperature range and strain value of the top slab was larger, and the trend of dynamic change was shown in a short time, which had obvious correlation with the temperature change. The results of regression analysis showed that the strain obeyed a sinusoidal function with the acquisition time, shown as in Eq. (1). Where, $\varepsilon$ expressed stress of main girder sections; $T$ was structure temperature collected of corresponding sections; $a$, $b$, $c$ denoted regression coefficients. The square values of correlation coefficient $R^2$ were
between 0.9245 and 0.9450, and the regression analysis results of each measuring point were shown in Table 1.

\[ \varepsilon = a \sin \left( \frac{2\pi T}{b} + c \right) \]  

Figure 3. Stress and temperature curves of main girder key sections in 2019: (a) Upstream bottom slab of pier top sections in the lower side of No. 59 span; (b) Upstream bottom slab of pier bottom sections in the lower side of No. 59 span; (c) Upstream bottom slab of No. 59 mid-span sections; (d) Upstream top slab of No. 59 mid-span sections; (e) Downstream bottom slab of pier top sections in the higher side of No. 60 span.
Table 1. Regression results of strain value and collection time in 2019.

| No. | Measuring point position                                                                 | a      | b       | c      | $R^2$ |
|-----|------------------------------------------------------------------------------------------|--------|---------|--------|-------|
| 1   | Upstream bottom slab of pier top sections in the lower side of No. 59 span                | 228.7743 | 616.3475 | 5.8429 | 0.9315 |
| 2   | Upstream bottom slab of pier bottom sections in the lower side of No. 59 span              | 254.0601 | 619.0733 | 5.9140 | 0.9281 |
| 3   | Upstream bottom slab of No. 59 mid-span sections                                         | 287.5528 | 658.8407 | 6.0104 | 0.9248 |
| 4   | Upstream top slab of No. 59 mid-span sections                                             | 314.7982 | 699.0253 | 6.1257 | 0.9245 |
| 5   | Downstream bottom slab of pier top sections in the higher side of No. 60 span              | 217.4796 | 589.9035 | 5.7152 | 0.9450 |

4.2. Analysis of deflection of main girder

Figure 4 showed the mid-span deflection curves of No. 63, 65 and 66 spans in 2019. It can be concluded from Figure 4 that the deflection variation of No. 66 span was the most obvious, and value was 49.41mm at the end of June. Compared to 1, January data, the deflection values of No. 63, 65 and 66 spans were 7.19mm, 16.44mm and 1.05mm on December 31, respectively. The deflection of side span was the largest, and the closer the middle span was, the smaller the value was. The deflection of each span changed dynamically in a short time, and increased with the increase of temperature, which was related to the temperature.

![Figure 4. Relationship curves of different mid-span cross section deflection in 2019.](image)

4.3. Typical crack state

The maximum crack expansion value was 0.09mm at the web of No. 63 span, and the maximum crack closure value was 0.17mm at the web of No. 59 span. The crack width fluctuated up and down in a certain range, which belonged to respiratory crack and had obvious correlation with temperature.

5. Conclusion

Based on the measured data of middle span deflection, key section strain and typical crack width, this paper studied the temperature effect of the main girder structure of strengthened Dongming Huanghe River Highway Bridge in service. The main research results are as follows:

1. Compared with the bottom slab, the top slab temperature range was larger, and the range of strain value was also wide. In a short period, the strain value fluctuated up and down with temperature, which had obvious correlation with temperature. The results of regression analysis showed that the strain obeyed a sinusoidal function with the acquisition time, and the square values of correlation coefficient $R^2$ were between 0.9245 and 0.9450.

2. The mid-span cross section deflection of side span changed most obviously, and the maximum value occurred from June to August. The deflection of side and secondary span was the largest, and the closer to the middle span was, the smaller the deflection was. The deflection of each span changed dynamically in a short time, and increased with the increase of temperature, which was related to the temperature.
(3) The crack width fluctuated up and down in a certain range, which belonged to respiratory crack and had obvious correlation with temperature.

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