Study on Mechanical Properties of Main Girder of Continuous Box Girder Bridge Strengthened By A Cable-Stayed System

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Abstract. The local stress concentration of the main girder during the tensioning construction of the continuous box girder bridge strengthened by the cable-stayed system is more prominent, which may lead to the sudden damage of the structure. Therefore, this paper studies the key section stress and deformation of the main girder in combination with the real bridge test. The results show that the maximum tensile and compressive stress increase of the main girder appears at the root floor and mid-span floor; The tensile action strengthens the compressive stress between the anchorage point of the long cable and the anchorage point of the short cable to the top of the pier, which releases some of the compressive stress across the mid-slab, improves the stress state of the main girder, and improves the shear load of the main girder ability; With the increase of the cable force, the main tensile stress of the web in the anchoring area first increases and then decreases. The lifting amount of the mid-span section of the main girder accounts for 20.06% of the total deflection, and the effect of the cable-stayed system on improving the deflection of the main girder is obvious.

1. Introduction

The Dongming Yellow River Highway Bridge started construction in October 1991, and it was completed and opened to traffic in October 1993. After 4 years of operation, cracks and deflections of the girder body were found. Since 1997, the cracks of the main bridge box girder and the alignment of the bridge decks were monitored. During this period, it was found that cracking and deflecting disease continued to develop and worsen. The main diseases include: oblique cracks distributed at the web L / 4 ~ 3L / 4, and various deflections appeared in each span. The maximum deflection detected in 2002 is 17.3cm. Aiming at the two diseases of cracking of the girder body and span-to-center deflection, the bridge was reinforced in 2003 by increasing the cross section of web, adding extra cables inside the box and setting the diaphragm to strengthen the integrity of the box girder [1, 2].
The reinforcement scheme of the cable-stayed system can improve the shear bearing capacity of the main girder and lift the mid-span height. The advantages of strengthening the long-span continuous box girder bridge are obvious [3, 4]. Dongming Yellow River Highway Bridge is the first long-span continuous box girder bridge reinforced with a cable-stayed system in China. Compared with other methods of reinforcement [5-7], the reinforced construction process of the cable-stayed system is more complicated and the local stress concentration of the main girder is more prominent due to the tensioning construction, which may lead to the sudden damage of the prestressed concrete continuous girder bridge structure strengthened by the cable-stayed during the tensioning phase. In order to ensure the safety of the structure during the tensioning construction process, the entire process is tracked and monitored for each working condition during the test to ensure the safety of the structure in the construction [8].

2. Main girder stress monitoring
Formulating a reasonable, safe and efficient tensioning scheme, and accurately controlling the tension cable force are the key factors to ensure that the deformation and stress of the main girder are within a reasonable range. The tensile force of the long and short cables is 2700kN and 2100kN. According to 30%, 50%, 65%, 75%, 85%, 90%, 95%, 100% of the designed cable force, the tension is divided into eight levels. Symmetric tensioning is performed according to the tension sequence from the middle tower to the side tower and from the long cable to the short cable. A total of 47 test sections are arranged throughout the bridge. The stress points of 63#–65# main girder are arranged as shown in Figure 1 and the conventional stress sections of main girder are arranged as shown in Figure 2.

![Figure 1. Layout charts of stress test of main girder section (Unit:cm)](image1)

![Figure 2. Layout of measuring points for root stress section of main girder](image2)

3. Main girder alignment monitoring
The alignment monitoring points of the main bridge are arranged on the top plate of the main girder, each monitoring cross section is symmetrically arranged with 2 measuring points along the center line of the main girder. Along the longitudinal direction of the bridge, they are arranged on the pier top section, 1/8-section, the long and short cable anchorage area section and mid-span section, each of the sensing lines are arranged with 67 measuring points, a total of 134 measuring points are arranged. Figure 3 is the layout of the measurement points of 58 # span and 59 # span. Among them, the 60 #,
61 #, 62 #, 63 #, 64 # and 65 # span are arranged in the same way as 59 # span, and 66 span is arranged in the same way as 58 # span.

Figure 3. Layout of alignment monitoring section of Dongming Huanghe River Highway Bridge

4. Monitoring results of main girder stress and deformation

4.1. Main girder stress monitoring results
The stress increment at the top and bottom points of the main girder under different cable tension is shown in Figure 4. In the figure, P is the design value of the cable force of the bridge. The number of the measuring points is 58 ~ 66, which indicates the span. The first letter D indicates a low pile, G indicates a high pile, Z indicates a span, and the second letter G indicates the root. D indicates a short cable, and C indicates a long cable. For example, 59-D-C indicates the stress value of the corresponding measuring point of the long cable of No. 59 span low pile.

Figure 4. Stress increment of top and bottom slab measured points under different tensioning phases
It can be seen from the figure that the stress increment of the top and bottom stress are antisymmetrically distributed with the abscissa as the axis. When tensioned to 0.75P, the maximum increment of tensile stress at the root floor measurement point 62-DG is 6.08 MPa. Further tensioning may cause the risk of cracking at the root section of the box girder. Therefore, the bridge deck is paved after tensioning to 75% of the design cable force. By adjusting the construction plan, the tensile stress increment of the root section of the main girder is significantly reduced and the maximum tensile stress increment when tensioned to 0.9P is 2.87 MPa, which appears at the measurement point 65-D-G; The measured point of the mid-span section top in the tensioning stage shows the tensile stress increment, with a maximum tensile stress increment of 3.49 MPa. At the same time, the mid-span top releases compressive stress as the cable force increases. The cable tension increases the pressure stress reserve of the measurement point of the root section top. The measured maximum pressure stress increment is 4.43 MPa, which appears at the measurement point 64-G-G. The corresponding increment of the pressure stress on the mid span floor is 5.49 MPa, which appears at the measurement point 59-Z. The short cable top in the anchoring zone shows compressive stress, the bottom plate is opposite, the long cable top is tensile stress, the bottom plate is opposite, and the stress increment is distributed in a "scissor shape". The maximum tensile stress increment of the top plate in the anchoring zone is 2.26 MPa, the maximum tensile stress of the floor plate is 3.42 MPa, and the maximum compressive stress of the top plate is 3.72 MPa, the maximum compressive stress of the floor plate is 4.15 MPa, both of which are all smaller than the maximum tensile and compressive stress increment of the main girder.

Figure 5 shows the measured values of the main tensile stress of the web plate under different tensile cable forces. It can be seen from the actual measurement results that the main tensile stress increment of the web at the 62-D measuring point under 0.3P is the largest, with a value of 0.98 MPa; Compared with other span measuring points, the main tensile stress increment of 62 and 63 span measuring points (middle span) are larger; After the completion of the tensioning construction (i.e. 0.9P tensioning stage), the main tensile stress increment at the 63-D measurement point is the largest, and its value is 0.11 MPa. In general, the main tensile stress increment of the web in the anchorage zone reinforced by the cable-stayed system is a change process that first increases and then decreases, and the main tensile stress increase in the middle span is large.

Figure 5. Comparisons between measured and calculated values of principal tensile stress at web measuring points

4.2. Main beam deformation monitoring results

Figure 6 shows the measured results of the deformation of the main girder under different tension cables. The deformation of 0.85P and 0.9P tension stage in the figure eliminates the influence of the bridge deck pavement on the deformation of the tension construction. As can be seen from the figure, the mid-section of 59 # has the largest lifting amount, with a value of 53.69mm. Secondly, the 65 # span lifts 45.22mm, and the 60 # ~ 64 # span lifts between 32.39 ~ 39.70mm. The other measuring
points all had different degrees of lifting, but the 58 # secondly side span was flexed downward at the initial stage of tension, and its lower deflection value was 9.13mm.

![Graph showing main girder deformation](image)

**Figure 6.** Measured results of main girder deformation

### 5. Conclusion

The local stress concentration of the main girder is more prominent during the tensioning construction of the continuous box girder bridge reinforced by the cable-stayed system, which may cause sudden damage to the structure. Therefore, this paper studies the key section stress and deformation of the main girder in combination with the actual bridge test. The main research results are as follows:

1. The maximum tensile and compressive stress increment of the main girder appears at the root plate and mid-span plate, which is one of the key positions for the monitoring of cable-stayed reinforcement. Compared with the root section, the compressive stress reserve of the section of the anchoring area is relatively small, which is also a key position of monitoring.

2. The tensile action strengthens the compressive stress between the bottom plate of the long cable anchoring point and the anchor point of the short cable to the top of the pier, releases a part of the compressive stress across the mid-span top plate, improves the stress state of the main girder, and improves the shear-bearing capacity.

3. With the increase of the cable force, the main tensile stress of the web in the anchoring area increases first and then decreases, and the main tensile stress increases in the middle span.

4. The maximum lifting capacity of the mid-span section is 53.69mm, and the lifting capacity of the mid-span section of the main girder accounts for 20.06% of the total deflection. The cable-stayed system has obvious effect on improving the deflection of main girder.

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