Study on mechanical behavior of new steel members of cable-stayed strengthening system

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Abstract. In the tensioning construction of continuous box girder bridge strengthened by a stay cable system, local stress concentration of steel joist and bracket is easy to be caused. This paper studies the stress and deformation of key section of steel joist and bracket by combining with real bridge test. The results show that the maximum stress of steel joist and bracket is less than the allowable stress. When the tensioning force value is 2.66 times of the completion cable force, the bottom plate first reaches the yield strength, and the stress change law of the bracket is not strong. The mid-span deformation of the steel joist in the early period of tensioning is gentle, and the change in the later period is large. When the tensioning force reaches the completion cable force, the value is about 1/400 of the span. In the early tensioning period, the relative displacement between the steel bracket and the girder is large, but the change in the later tensioning period is not large.

1. Introduction

Because the strengthening method of cable-stayed system can improve the shear capacity of the girder and the height of the mid-span section [1, 2], Dongming Yellow River Highway Bridge adopted this system in December 2014 [3]. Its general structure is added on both sides of the original pile foundation. In the pylon tower, a steel joist beam is laterally added to the lower part of the girder, and the steel joist beam and the girder are connected at an anchorage zone at the bottom of the box girder through a joint joint, and the stay cable is anchored from the pylon tower to the steel joist beam, and the cable force of the cable stays through the steel The joists and the joints are coupled to the girder [4]. Among them, the steel joist and bracket play an important role in the cable-stayed system, and are important members connecting the cable and girder, which are related to the structural safety of the whole bridge. Before strengthening, numerical simulation and model test were used to study the steel joist and bracket, analyzed the stress of the steel joist and bracket structure in the period of tensioning construction, and found out the most unfavorable parts of the steel joist and bracket [5]. Therefore, according to previous studies, stress sensors and deformation measurement points are arranged in the real bridge test to ensure the safety of the steel joists and brackets.
2. Stress monitoring of new steel members

2.1. Main girder stress monitoring results

Thirty-two steel joists were added to the whole bridge, sixteen of which were selected for stress monitoring. The stress test section of the steel joists arranged longitudinally along the bridge is the same as that of the girder, with a total of thirty-two sections. According to the test results of the scale model test [5], eight measuring points are arranged for each steel joist, and the top and bottom measuring points are 4.5m apart from the mid-span of the steel joist. The specific measuring points are shown in Figure 1. 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 [6]. Figure 2 and 3 show the stress increment at the top and bottom slab measuring points of steel joist under different tensioning forces, respectively. The average value of 4 measuring points is used as the stress increment value. 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.

![Diagram of steel joists measuring point arrangement (Unit:mm).](image1)

![Measured results of stress at measuring points of joist bottom slab.](image2)
It can be seen from the measured results that the maximum stress increment of the top slab of the steel joist is -103.69 MPa, and the maximum stress increment of the bottom slab is 86.35 MPa, both smaller than the allowable stress of the steel joist. Compared with the measured value, the finite element analysis result is larger, but the stress change rule of the measuring point of the steel joist is basically consistent with the theoretical result. Figure 4 shows the stress increment regression results at each measuring point at the top and bottom slab of the steel joist. It can be seen from the figure that the stress value of the steel joist increases linearly with the increase of tensioning force, indicating that the steel joist is in the elastic period. The linear regression equations of stress increment at the top and bottom of the steel joist are \( \Delta \sigma_{t} = 90.4383P - 13.6885 \) and \( \Delta \sigma_{b} = -121.5496P + 21.1509 \). \( \Delta \sigma_{t} \) represents the stress increment at top slab of steel joist; \( \Delta \sigma_{b} \) represents the stress increment at bottom slab of steel joist.

From the linear regression results, when the tensioning force is 2.66 times of the completion cable force, the bottom slab first reaches the yield strength. The test results of real bridge are basically consistent with the model test results, which verifies the safety of the steel joist [5].

2.2. Stress monitoring results of steel brackets
According to the results of model test, the safety storage of steel brackets is relatively large. In the real bridge test, two brackets (62-D-C and 58-G-D) are selected for the test. The measuring points of J1~J10 were mainly arranged on the stiffener of the steel bracket, in which the short cable and long cable steel bracket were arranged in the same position, and the measuring points were arranged as shown in Figure 5.
Figure 5. Layout of bracket stress measuring points.

Figure 6 and 7 show the measured values of the stress increment at the measuring points of short cable and long cable in the steel joist under different construction stages. Among them, the stress increment at the measuring points of short cable J7 is the largest with a value of -85.02 MPa, and that at the measuring points of long cable J1 is the largest with a value of -89.05 MPa, both smaller than the allowable stress at the steel bracket. Compared with the real bridge and model test results, the finite element analysis results are larger, and the maximum stress is -146.87 MPa.

Overall, the stress at the measuring points of the bracket does not change strongly with the increase of tensioning force, which is related to the processing accuracy, assembly quality and tension balance control of the new steel members. The application of steel bracket (connection joint) in real bridge shows that the structure shape of joint in anchorage area should be as simple as possible, and the structure force should be as clear as possible, which is helpful to the analysis of joint stress transfer mechanism under the combined action of compression and shear, and also the application of joint in real bridge.
Figure 7. Measured results of stress at 62-D-C bracket measuring points.

3. Linear detection of new steel members
In this paper, 59-D-C and 61-G-C positions are selected to arrange measuring points for the displacement of steel joists. Three measuring points are arranged for each group of steel joists, and a total of six measuring points are arranged for the whole bridge. In addition, relative displacement measurement points are arranged on the side of each bracket and the web of the girder, and a total of sixty-four measuring points are arranged on the whole bridge. Figure 8 shows the relationship between mid-span deformation of joists and tensioning cable force at positions 59-D-C and 61-G-C. Figure 9 shows the relative displacement between the steel bracket and the girder under different tensioning forces, in which the relative displacement of the two brackets on the same cross-section is selected as the average value of the relative displacement.

Figure 8. Relationship between mid-span deformation of joist and tensioning force.
As can be seen from Figure 8, the mid-span deformation of the steel joist in the early tensioning period is gentle, while that in the late period is relatively large. The maximum mid-span deformation of 61-G-C steel joist at position is 52mm, about 1/400 of the span. The maximum mid-span deformation of 59-D-C steel joist is 35mm, about 1/600 of the span.

As can be seen from Figure 9, when the tensioning force is stretched to 0.3 times of the completion cable force, and the relative displacement between the steel bracket and the girder is relatively large. However, the relative displacement of 0.5-0.9 times of the completion cable force does not change much. The relative displacements of different measuring points are also not the same, which is related to the assembly and construction quality of the anchorage steel bracket and the tension balance control. Therefore, it is very important to improve the machining precision of steel bracket and the anchorage quality of girder anchorage zone.

4. Conclusion
In the tensioning construction of continuous box girder bridge strengthened by a stay cable system, local stress concentration of steel joist and bracket is easy to be caused. This paper studies the stress and deformation of key section of steel joist and bracket by combining with real bridge test The main research results are as follows:

1) The maximum stress of steel joist and bracket is less than the allowable stress. When the tensioning force is 2.66 times of the completion cable force, the bottom slab of steel joist first reaches the yield strength.

2) The stress change law of the bracket is not strong, which is related to the processing accuracy, assembly quality and tensioning balance control of the new steel members. Therefore, the connection joint structure should be as simple as possible, which is conducive to the analysis of the stress transfer mechanism of the steel joint under compression and shear

3) The mid-span deformation of the steel joist in the early tensioning period of is gentle, but the change in the later period is large. When the tensioning force reaches the completion cable force, the value is about 1/400 of the span.

4) In the early tensioning period, the relative displacement between the steel bracket and the girder is relatively large, and the relative displacement between different measuring points is also different. In the late tensioning period, change is little, which is related to the assembly quality of the steel bracket and tensioning balance control.

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