Analysis on the Causes of Cracks in Curved Box Girder Bridges with Small Radius

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Abstract. At present, curved box girder bridges with small radius is widely used in modern highway and urban road interchange flyover, especially in the design of ramp bridge of interchange flyover. Taking the ramp of Liaoyang Road to Haier Road Flyover in Laoshan District of Qingdao as an example, this paper calculates and compares the first principal stress at different positions of typical cross-sections by elementary beam theory and numerical calculation theory, and analyzes the mechanical reasons for serious cracks in the bridge.

1. Introduction
In recent years, the number of curved box girder bridges with small radius has been increasing year by year in modern highway and urban road flyover. Especially in the design of ramp bridge of interchange flyover it is more widely used. It is well known that, compared with straight beams, curved beams with small radius mainly have the following characteristics:
(a) The bending stress at the outer edge is greater than that at the inner edge.
(b) The deflection at the outer edge is greater than that at the inner edge, and the deflection difference increases with the decrease of curvature radius.
(c) No matter what kind of bearing arrangement is adopted, there is always torque in the curved beam.
(d) The permanent load inner force of each main beam is not uniform, so the curved beam is always in the state of coupled bending, shearing and torsion.
Because the curved box girder bridge with small radius is always in the state of complicated coupling of bending, shearing and torsion, the shear lag effect, restrained torsion warping effect and distortion effect of box section will affect the stress of the section, and the larger the beam stress is the likely to cause the beam cracks.

Taking the ramp of Liaoyang Road to Haier Road Flyover in Laoshan District of Qingdao City, Shandong Province as an example, this paper calculates and compares the first principal stress at different positions of typical cross-sections by elementary beam theory and numerical calculation theory, and analyses the mechanical causes for many serious cracks in the bridge.

2. Project overview
Liaoyang Road to Haier Road Flyover is a hub flyover located in Laoshan District, Qingdao, Shandong Province. The main bridge of the flyover is a continuous beam bridge, and the ramp is a curved continuous beam bridge with small radius. This paper focuses on the ramp of the flyover, which is located on a circular curve with a radius of 55m. The basic information of the ramp is as follows:

- Structure type: \((2 \times 23 + 2 \times 23)\) m reinforced concrete continuous box girder;
- Transverse layout: 0.5m (collision-preventing wall) + 7.5m (carriageway) + 0.5m (collision-preventing wall);
- Center curve radius: 55m;
- Strength grade of concrete: C45;
- Reinforcement grade: HRB335;
- Designed load level: City-A.

It is found that there are more transverse and oblique cracks in the main girder of ramp bridge, and the width of the cracks is larger. There are more vertical and oblique cracks in the web plate, the cracks are wide in the middle, narrow at both ends, and the number of cracks on the outer side of the beam body is more than that on the inner side. There are more and denser transverse cracks in the 1/4 ~ 3/4 span of the floor, the maximum width of which is 0.15 mm. And the results of structural check and calculation show that there is no problem of insufficient bearing capacity of beam body. In order to further explore the cause of the formation of cracks, the elementary beam theory and finite element numerical calculation are carried out to analyze the characteristics of stress distribution of the ramp bridge.

3. Calculation and Analysis

In order to explore the causes of the formation of the cracks, the beam-element model and the solid-element model of the ramp bridge are established respectively through the finite element calculation software --- Civil and MIDAS FEA, and the structure of the ramp bridge is calculated. The stress distribution at different positions of the first span of the bridge is calculated by selecting three typical cross-sections: 1/4 cross-section, 1/2 cross-section and 3/4 cross-section, and the stress gives the calculation results of the bending theory of the primary beam. Taking the shear-lag effect, restraint torsion warpage of box girder and the calculation of distortion effect into consideration, the effects of shear-lag, warpage and distortion of curved box girder bridge with small radius are calculated by numerical analysis. By comparing the difference of two kinds of stress and combining the tensile property of the material, the cause of crack formation is analyzed.

In the calculation, structural deadweight, secondary dead load, overall temperature difference \((\pm 22^\circ C)\), the temperature gradient load and city-A class automobile load are considered. The first principal stress values of elementary beam theory and numerical analysis theory are calculated by selecting 6 points, as shown in Figure 1, on 1/4, 1/2 and 3/4 cross-sections respectively. As shown in Table 1 ~ Table 3.

**Figure 1. Cross-sectional profile of typical section**
Table 1. First Principal Stress of 1/4 cross-section (Unit: MPa).

| Method of calculation       | 1    | 2    | 3    | 4    | 5    | 6    |
|-----------------------------|------|------|------|------|------|------|
| Elementary Beam theory      | 0.00 | 0.01 | 0.34 | 0.35 | 5.38 | 5.43 |
| Numerical calculation (solid element) | 1.21 | 0.84 | 10.01| 2.28 | 5.60 | 5.30 |

Table 2. First Principal Stress of 1/2 cross-section (Unit: MPa).

| Method of calculation       | 1  | 2  | 3  | 4  | 5  | 6  |
|-----------------------------|---|---|---|---|---|---|
| Elementary Beam theory      | 0.03 | 0.05 | 0.52 | 0.22 | 5.16 | 5.27 |
| Numerical calculation (solid element) | 1.22 | 0.96 | 12.54 | 8.22 | 7.22 | 7.29 |

Table 3. First Principal Stress of 3/4 cross-section (Unit: MPa).

| Method of calculation       | 1  | 2  | 3  | 4  | 5  | 6  |
|-----------------------------|---|---|---|---|---|---|
| Elementary Beam theory      | 2.13 | 2.81 | 1.49 | 0.98 | 0.09 | 0.12 |
| Numerical calculation (solid element) | 1.16 | 1.63 | 2.77 | 2.24 | 1.02 | 1.31 |

Through the comprehensive analysis of the bending theory and numerical calculation results of primary beams, we get the following findings:

(a) The numerical results of the first principal stress at 1, 2, 3 and 4 points of the cross-section are obviously larger than the theoretical results of the primary beams, which shows that it is unfavorable to the girder considering the shear-lag effect and the torsion warpage and distortion effect of curved girder bridge, it is easier to cause the cracking of the concrete of the girder, and the shear-lag effect of box girder and the warpage and distortion effect of curved girder bridge should not be neglected.

(b) The maximum first principal stress appears at the neutral axis (3 and 4 points), and the outer side is larger than the inner side; the first principal stress at the neutral axis of 1/2 cross-section is 12.54 MPa on the outer side and 8.22 MPa on the inner side, and the first principal stress at the neutral axis of 1/4 cross-section is 10.01 MPa on the outer side and 2.88 MPa on the inner side, which are all larger than 2.51 MPa, the standard value of tensile strength of C45 concrete. The first principal stress on the web is generally the resultant stress of direct stress and shear stress, and the direction is obliquely intersected with the beam body. When the principal tensile stress of the concrete structure is greater than the tensile strength of the concrete, the neutral axis appears firstly at the cracks perpendicular to the first principal stress, then extends to both ends, which are also the mechanical reasons that the inclined crack on the web develops obliquely, the middle is wide and the two ends are narrow, and the crack on the outside web is serious.

(c) At the bottom of the cross-section (5 and 6 points), the first principal stress is larger, the stress on both sides of 1/4 and 1/2 cross-sections are greater than 5.0 MPa, and the standard value of tensile strength of C45 concrete is 2.51 MPa. The direct stress at the bottom of the cross-section is larger, so the cracks develop laterally.

Based on the above analysis and calculation results, the distribution law of the cracks in the beam of the ramp bridge of the Liaoyang Road-Haier Road Flyover is in good agreement with the distribution law of the first principal stress, it can explain the reason of the beam body crack of the ramp, and it can be concluded that the beam body crack of the ramp is mainly caused by the structure stress.

4. Conclusion
Taking a real bridge as an example, this paper calculates and compares the first principal stress at different positions of typical cross-section by elementary beam theory and numerical calculation theory. In addition, the following should be given full attention in engineering practice:

(a) Although the load-bearing capacity of curved box girder bridge with small radius meets the design requirements, the stress distribution is affected by warpage torsion and distortion effects, the stress distribution is quite different from the theoretical results of the primary bridge, and it is difficult to avoid the cracks when the bearing capacity meets the design requirements.

(b) The force of curved box girder bridge with small radius is more complicated than that of straight beam bridge for coupling action of bending, shearing and torsion, so the adverse effects of shear lag, warpage torsion and distortion should not be neglected in the design calculation;

(c) The cracks in the beam body will not reduce the bearing capacity of the bridge to a great extent, but the wider cracks will affect the durability of the bridge. So reasonable treating measures should be put forward to deal with the cracks in time.

References
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