Girder Lattice Model and Single Beam Model In Load Test of Continuous Box Bridge Computational Comparison and Analysis

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Abstract. The static load test of a three-span continuous box girder in Huzhou City, Zhejiang Province is analyzed and calculated by using the grillage method and the single main girder method. The rationality of the two calculation models is compared with the field load test data. The calculation results show that the results of grillage method are more consistent with the experimental results than that of single girder method, and the safety of the calculation results is higher. Therefore, in the load test of multi-compartment box girder bridge, the grillage method is more reasonable and can better reflect the mechanical characteristics of the bridge structure.

1. Introduction
In recent years, with the rapid development of highway traffic in China, box girder bridges have good mechanical properties and economic advantages. When the span of bridges exceeds 30 meters, box section is almost the first choice for bridge designers and investors. Midas Civil is often used to establish calculation model for box girder static load test. The common methods for calculating bridge model are single beam method and grillage method. In the static load test of box girder bridge, the stress of box girder and the deflection data of both sides of bridge deck are the focus of attention. The single beam method uses the single-heel main beam model for discrete analysis, and calculates the internal force based on the transverse distribution theory. The results of bridge internal forces calculated by this method will vary greatly with the different values of load transverse distribution coefficient[1]. For the superstructure of sub-format bridges, the beam-grid method can be used to establish the spatial bar system model[2]. The shear-flexible grillage method can be used to analyze the concrete box girders which are widely used in cities and highway bridges[3-6]. Taking a 3-span continuous box girder as an example, combined with field static load test, the difference of internal force results between the two calculation models is analyzed and the rationality of the two models is analyzed.

2. Engineering survey
A three-span (21m+30m+25m) continuous box girder bridge in Huzhou City, Zhejiang Province, is transversely arranged with 0.5m anti-collision barrier, 15.5m lane and 0.5m anti-collision barrier. The upper structure adopts pre-stressed concrete continuous box girder, the concrete grade of the main girder is C50, the lower structure adopts column pier, column abutment and bored pile foundation, and the deck pavement adopts 1cm thick concrete C50 cushion and 10cm thick asphalt concrete, the bridge facade as shown in Figure 1:
The main girder height of the bridge is 1.8m, the transition section from 0.25 to 0.35m, the roof transition section from 0.28 to 0.48m, and the web transition section from 0.45 to 0.66m. The section form is shown in the figure 2:

3. Single girder model
Because the superstructure of the bridge will bend and twist along the longitudinal direction under the action of load, and the transverse deformation does not change its shape, the superstructure can be considered as a longitudinal main beam. This model concentrates the mass (translational mass and rotational mass) and stiffness (vertical, transverse flexural stiffness and torsional stiffness) of the whole bridge on the intermediate elements and joints. The single beam model established in this paper consists of 90 nodes and 87 elements. The model structure is shown in Figure 3:

4. Coupled vibration vehicle model

4.1. Basic principles of girder method
The box girder section can be regarded as a combination of several I-section sections connected by the top and bottom plates. When the bridge deck is very wide or irregular, or when irregular loading is caused by the bifurcation of lanes, the internal forces of each I-beam will be different[7]. At this time, in order to obtain more accurate internal forces of each beam, many longitudinal elements can be used to simulate I-beam. At the same time, some transverse elements are added to simulate the transverse connection between I-beams. Sometimes, some virtual elements are introduced for the convenience of loading to form a plane grid. The nodes on these grids can be used to simulate the bridge deck for the convenience of loading. In this way, the plane grid structure composed of a series of intersecting elements is used to carry out the stress analysis of box girders, that is the beam grillage method. The model structure is shown in Figure 4:
4.2. Computational Section Characteristics

According to the relevant theoretical formulas, the cross-section characteristics of each grid element, including cross-section area, bending moment of inertia, shear area, torsional moment of inertia and other parameters [8-9].

According to the cross section division diagram of the beam grid, the area, bending moment of inertia and shear area of each longitudinal unit are the area, bending moment of inertia and shear area of corresponding I-beam. Under load, the top and bottom plates of box girder will bend laterally around the neutral axis. As shown in the figure, the transverse elements connect the longitudinal elements like a shear rigid web. This transverse bending deformation does not take into account the torsional deformation of the cell caused by the single bending of the top and the bottom. The formulas for calculating moment of inertia per unit transverse element are as follows:

$$I_t = \frac{h_1^2d_1^2 + h_2^2d_2^2}{d_1 + d_2}$$

In the formula: $h_1$ is the distance from the top to the center of shape; $h_2$ is the distance from the bottom to the center of shape; $h$ is the distance between the top and the bottom; $d_1$ is the thickness of the top; $d_2$ is the thickness of the bottom.

If the shear force is assumed to be proportional to the bending stiffness between the roof and the floor, and there is a reverse bending point at the midpoint between the webs. Then the shear area of transverse element with unit width can be obtained. The formulas for calculating the shear area of transverse element with unit width are as follows:

$$A_s = \frac{d_1^2 + d_2^2}{I^2} \left[ \frac{d_u}{d_u + \left( d_1^2 + d_2^2 \right)} \right] \frac{E}{G}$$

In the formula, $l$ is the spacing between adjacent webs; $d_u$ is the width of webs; $E$ and $G$ are the compression and shear modulus of elasticity of materials respectively.

The cross-section torque is mainly supported by the top, bottom and web, so the cross-section torsional inertia moment of each unit width longitudinal and transverse element is as follows:

$$I = 2 \left( h_1^2d_1 + h_2^2d_2 \right) = \frac{2h^2d_1d_2}{d_1 + d_2}$$

For the standard section, the average thickness of both sides of the diaphragm beam and the real section of the diaphragm beam should be taken into account for the longitudinal element at the diaphragm beam, while the average thickness of the two sides of the diaphragm beam can be used for the transverse element.
5. Analysis condition
In addition to the differences in modeling methods, the other control factors of the two models must remain the same. Only by ensuring that the two models are compared under the same load conditions can the reliability of the test results be guaranteed. The load considered in this paper mainly includes the second-stage dead load of box girder, bridge deck pavement and test vehicle load. Test conditions and test sections are determined by the most disadvantageous stress principle and representative principle of bridge structure. In this paper, the second and third spans are selected for calculation and load test. According to JTG D60-2015 "General code for design of highway bridges and culverts", loading arrangement of vehicle load is carried out. Lane load is used in the two calculation models. Eight 29t standard three-axle vehicles were used to load the second and third span of the test span in each working condition of the field test.

By comparing the deflection, stress and field test data of single beam model and grillage model under the same load condition, the deviation of the calculated results of the two models is analyzed in the Madas Civil calculation software. Load test conditions are as follows: 1) 1st working condition: maximum positive bending moment of the third span, mid-load of the transverse bridge; 2) 2nd working condition: maximum positive bending moment of the third span, biased load of the transverse bridge; 3) 3rd working condition: maximum positive bending moment of the second span, mid-load of the transverse bridge;4) 4th working condition: maximum positive bending moment of the second span, biased load of the transverse bridge; 5) 5th working condition: negative bending moment near pier top, biased load of the transverse bridge. Loading arrangement of each working condition is shown in Figure 6:

![Figure 6. Loading diagram under load condition](image)

Static load test determines the size and layout of test load according to load efficiency of static load test. The efficiency of static load test should be between 0.85 and 1.05 for acceptance of intersection (completion) works. \( \eta \) should be calculated according to the following formula:

\[
\eta = \frac{S_t}{S(1 + \mu)}
\]

In the formula, \( S_t \) is the maximum calculated effect value of the internal force or displacement of the load control section corresponding to a load test item under the action of static load test; \( S \) is the calculation value of the most unfavorable effect of internal force or displacement of the same control section under control load; \( \mu \) is the value of impact coefficient.
6. Layout of test points
The main content of bridge static load test measurement is the numerical change of deflection and stress of test section of box girder under various load conditions. Through the comparative analysis of the theoretical calculation value of the model and the measured value of the field static load test, we can judge whether the structural rigidity and performance of the bridge meet the design requirements. Through the way of installing strain gauge on the web and bottom plate of the box girder in the test section, the strain gauge is arranged along the bridge direction, that is, the strain gauge test direction is consistent with the main stress direction of the component, and the test section is respectively set at the section with the maximum positive moment of the second and third span and the section with the maximum negative moment of the third pier top respectively. The deflection measuring points are arranged at the edge of both sides of the carriageway, and the high-precision level is used for deflection measurement. The arrangement of strain and deflection test points of the cross-section tested at midspan and fulcrum are shown in the figure 7:

![Figure 7. Layout of measuring points](image)

7. Comparison and analysis of model results and experimental data

7.1. Contrastive analysis of bending moment
Field Load Test is carried out by means of the maximum bending moment value of each working condition. The maximum bending moment values of working condition 1, 2, 3 and 4 occur in the middle of the corresponding test span[10]. The minimum bending moment values of working condition 5 occur near the 2nd bearing, which conform to the bending moment distribution of three-span continuous beam. The influence lines of working conditions on the maximum bending moment are shown in the Table 1.

Under the action of working conditions 1 to 5, the relative errors of bending moment values of the two calculation models are 1.29%, 0.78%, 2.45%, 2.00% and 0.23%, respectively. The comparison of bending moment values under different conditions is shown in the table 1. Generally speaking, the calculated bending moments of the grillage model are slightly larger than those of the single beam model.

| Load working condition | Single beam model / (kN·m) | grillage model / (kN·m) | relative error /% |
|------------------------|-----------------------------|------------------------|------------------|
| 1                      | 7960.19                     | 8063.67                | 1.29             |
| 2                      | 8133.34                     | 8196.78                | 0.78             |
| 3                      | 7402.21                     | 7583.35                | 2.45             |
| 4                      | 7775.69                     | 7931.21                | 2.00             |
| 5                      | -5249.37                    | -5261.23               | 0.23             |

7.2. Comparative analysis of strain
In the load test of the prestressed concrete continuous box girder, the important basis of the performance evaluation of the box girder lies in its stress distribution law and relevant numerical value.

In load test, strain data are collected by installing strain gauges on the test sections of box girder webs and bottom plates. The strain values of the corresponding strain test sections and the measured strain values of the field load test in the two calculation models under different working conditions are shown in the figure 8. From the numerical point of view, the theoretical strain values of the two calculation models are larger than the measured values of the load test, which indicates that the actual structural stiffness of the bridge meets the requirements; the theoretical calculation values of the grillage model
are larger than the theoretical calculation values of the single girder model. The change of strain data in each position of the section in the beam grid model is more in line with the change rule of the field strain measured data in the load test. However, the theoretical strain values of the single beam model are almost constant and close to the horizontal straight line at each test section. In contrast, the grillage model can better reflect the stress characteristics of the box girder.

Figure 8. Comparison of strain results

7.3. Contrastive analysis of deflection
The deflection values of the two models under the same working condition are compared and analyzed with the calculation results of the single beam model are shown in the Table 2.

1) The results of deflection calculation under load working condition 1 show that the maximum deflection of single beam model and grillage model occurs near midspan, the maximum vertical deflection of single beam model is 2.591 mm, the maximum vertical deflection of grillage model is 2.643 mm, and the relative error of moment values of the two models is less than 2.01%.

2) The results of deflection calculation under load working condition 2 show that the maximum deflection of the single beam model and the grillage model occurs near the side span. The maximum
vertical deflection of the single beam model is 2.706 mm, the maximum vertical deflection of the grillage model is 2.757 mm, and the relative error of the moment values of the two models is less than 1.88%.

3) The results of deflection calculation under load working condition 3 show that the maximum deflection of single beam model and grillage model occurs near midspan, the maximum vertical deflection of single beam model is 3.151 mm, the maximum vertical deflection of grillage model is 3.181 mm, and the relative error of bending moment of the two models is less than 0.95%.

4) The results of deflection calculation under load working condition 4 show that the maximum deflection of the single beam model and the grillage model occurs near the side span, the maximum vertical deflection of the single beam model is 3.449 mm, the maximum vertical deflection of the grillage model is 3.556 mm, and the relative error of the moment values of the two models is less than 3.10%.

5) The test section of load working condition 5 is near the bearing, and the deflection of the bearing test section is too small to change obviously, so it is omitted.

The field deflection measurements for different working conditions and the comparison of the maximum deflection values under different working conditions are shown in the Table 3.

Table 2 The measured deflection of load test under various working conditions

| Load working condition | Measuring point number | 1# | 2# | 3# |
|------------------------|------------------------|----|----|----|
| 1                      |                        | -1.913 | -2.348 | -2.092 |
| 2                      |                        | -2.527 | -2.273 | -1.938 |
| 3                      |                        | -2.781 | -3.025 | -2.543 |
| 4                      |                        | -3.254 | -2.596 | -2.487 |

Table 3 Maximum Deflection of Load Test under Various Working Conditions

| Load working condition | Single beam model (kN·m) | Grillage model (kN·m) | Measured data /mm | Relative error /% |
|------------------------|---------------------------|-----------------------|-------------------|-------------------|
| 1                      | -2.591                    | -2.643                | -2.348            | 2.01              |
| 2                      | -2.706                    | -2.757                | -2.527            | 1.88              |
| 3                      | -3.151                    | -3.181                | -3.025            | 0.95              |
| 4                      | 3.449                     | -3.556                | -3.254            | 3.10              |

Through the analysis of the above two tables, Under the action of various load conditions, the deflection trend of the two calculation models is basically the same. The relative error of the maximum deflection value of the two models is within 3.10% and the calculation value of the grillage model is slightly larger than that of the single beam model. From the engineering point of view, the calculation of the grillage model is more safe and more in line with the structural characteristics, so it can be considered that the application of grillage model can meet the requirements of continuous connection requirements for calculation accuracy of continuous box girder.

8. Conclusion

(1) The strength of the transverse support of the finite grillage model has a great influence on the internal force distribution of the calculation model. When the bridge is subjected to torsion, the normal stress caused by the restraint torsion of the box girder section and the distortion are not taken into account in the calculation process.

(2) Under various load conditions. The distribution trend of bending moment, strain and deflection of grillage model and single beam model is basically the same, but the calculation result of grillage method is bigger and the safety is higher. Therefore, it is more reasonable to select the grillage model to analyze the load test results of continuous box girder bridges. At the same time, the grillage model can better reflect the mechanical characteristics of the structure, and the grillage method has greater advantages in the analysis and calculation of complex bridge types.
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