Research on Mechanical Behavior of Prefabricated I-Section Reinforced Concrete Slab Girder

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Abstract. Cracks, water seepage and other damage often occurred in the hinge joints of the fabricated hollow slab bridge and affect the transverse integrity of the bridge. In order to solve these problems, a new type prefabricated I-girder is proposed, the girder is connected crosswise through wet joints, and the distributed bars extending from the flange are firmly connected in the wet joints. The wet joint has replaced the hinge joint in the traditional hollow slab structure. Through the static load test of the three-piece fabricated I-section slab girder model, the overall mechanical behavior and the transverse distribution of the load in the fabricated I-section slab girder bridge are studied. Then the dynamic characteristics and overall mechanical properties of the traditional hollow slab girder bridge and the fabricated I-girder bridge with equivalent section was analyzed by MIDAS, consider the influence of shallow hinge joints, middle hinge joints and deep hinge joints. The experimental results are compared with the numerical analysis results, the results show that, under the condition of equivalent section, the overall flexural stiffness and torsional stiffness of the fabricated I-section slab girder structure are greater than that of the traditional hollow slab structure, and the transverse distribution of the load is more uniform, the fabricated I-section slab girder structure has better mechanical performance.

1. Introduction
Hollow slab girder has been widely used in small and medium span bridges in China. The bridges that constructed by assembled prefabricated hollow slab girders are characterized by easy standardization of construction and superior stability of girders during transportation and hoisting [1]. Hinge joints are always adopted by hollow slab girder bridges. During the design process, the shear forces transmitted through the hinge joints should be mainly considered, and longitudinal cracks often occur at hinge joints under long-term repeated loads. When the hinge joint is damaged, the integrity of the assembled hollow slab girder bridge will decrease, and the transverse distribution of load changes. Especially when the failure ratio of hinge joint is large, the transverse connection between slab girders will fail, resulting in the occurrence of the dangerous condition of "single slab (beam) bearing force"[2]. In addition, it is difficult for the four supports at the bottom of each hollow slab girder to have the same...
heights, which easily leads to the void phenomenon of the supports. When the vehicle passes by, the slab girder of the support will warp, which easily causes the hinge joint breakage [3].

A series of researches on the stress mechanism, failure form, calculation theory, reinforcement measures and transverse load distribution law of hinge joints in hollow slab girder bridges have been conducted by many researchers. Based on design, construction and operation, the stress mechanism and failure modes of hinge joints of hollow slab girder bridges are studied by Qiao et al. [4], Liu et al. [5], and Huang et al. [6]. The calculation method of internal force of hinge joint is also studied by energy method [7] and analytic method [8]. Based on the mechanism of hinged joints, reinforcement measures such as enlarging size, applying transverse pre-stressing force, sticking fiberboard and increasing steel slab force transmission between hinged joints are developed [9-11]. In addition, through the study of the load transverse distribution law of reinforced concrete slab girders with hinged joints, the calculation methods of hinged joints, rigid joints, analogous orthotropic plates, rigid beams and elastically supported continuous beams are developed [12-15].

In order to solve the problems of poor articulated joints construction quality, insufficient resistance and void support in traditional hollow slab girder bridges, an improved prefabricated I-section slab girder is proposed in this paper. By connecting the wet joints between the upper and lower flange plates, the steel bars stretched out from the flange plates are firmly tied in the joints, and an integral force system with the same cross-section as the traditional hollow slab girder is formed. The integrity of the girder is ensured by the wet joint construction between adjacent prefabricated girders. At the same time, only two supports are needed at the bottom of each prefabricated girder, which avoids the problem that the four supports are easy to void. The mechanical properties of assembled I-shaped slab girders with single, two and three combinations under different levels of loads are tested. The mechanical properties of single girder, the overall performance of multi-girder and the transverse distribution of load of the new type of assembled slab girder are also analyzed. By comparing the numerical analysis results with the corresponding traditional hollow slab girder model, the advantages of the new slab girder in the overall mechanical performance, load transverse distribution, stiffness and other aspects are illustrated.

2. Experiments of assembled I-shaped SLAB girders

2.1. Design of the specimens

Three assembled I-shaped slab girders are designed, and the section size and reinforcement of specimen B1 are shown in Figure 1. The width, height and length of B1 are 50 cm, 37 cm and 500 cm, respectively. There are eight HRB400 longitudinal bars with a diameter of 12 mm on the bottom, and two HRB335 longitudinal bars with a diameter of 8 mm on the top. The stirrups and reinforced bars on the upper and lower flanges are HRB335 bars with diameter of 8 mm, spacing of 20 cm. The thickness of concrete cover is 3 cm.

The specimen B1 is a single prefabricated slab girder, B2 is a double composite slab girder, and B3 is a three composite slab girder. The cross section and size of B2 and B3 are shown in Figure 2. The refabricated slab girders of B2 and B3 are connected by wet joints of upper and lower flanges with a width of 20 cm. Distribution bars extending from adjacent flanges are tied in wet joints, and two longitudinal bars with 8 mm diameter are arranged.
Figure 1 Section size and reinforcement of specimen B1 (mm)

Figure 2 The section size of (a) B2 and (b) B3 (mm)

The test specimens are made of C40 concrete. The average cubic compressive strength is 43.8 MPa, and the elastic modulus is $3.25 \times 10^4$ MPa. The measured yield strength, ultimate strength and elastic modulus of longitudinal bar (HRB400) are 441.8 MPa, 606.3 MPa, and $2.1 \times 10^5$ MPa. The measured yield strength, ultimate strength and elastic modulus of stirrups (HRB335) are 351.0 MPa, 526.8 MPa, and $2.0 \times 10^5$ MPa.

2.2. Loading scheme

The test girder is supported by ordinary plate rubber bearing, the loading point of B1 is located in the middle span of the test girder. The loading point of B2 is located in the middle span of the right girder B. The load of B3 can be divided into three working conditions. In case 1, centralized load is applied to the mid-span of three split girders by distributing girders. In case 2, centralized load is applied to the mid-span of middle girder B. Additionally, centralized load is applied to the right side girder C in case 3. The detailed loading conditions of each specimen are shown in Table 1.

| Specimen | Number of branches | Loading position | load increment /kN | Maximum load /kN |
|----------|--------------------|------------------|---------------------|------------------|
| B1       | 1                  | Mid-span         | 5                   | 30               |
| B2       | 2                  | Mid-span of side girder | 5             | 35               |
| B3       | 3                  | Mid-span of three girders | 5             | 50               |
| B3       | 3                  | Mid-span of mid-girder | 5              | 50               |
| B3       | 3                  | Mid-span of side girder | 5              | 35               |
The loading was controlled by force, and preloading is firstly conducted. When loaded formally, the load is stable for 5 minutes at each stage, and the deflection of the girder is measured. In order to study the working state of the girder in the elastic stage, the crack development and crack width are closely observed during the test. When the lower flange crack extends to half the web height or the crack width exceeds the limit, the test shall be stopped.

A displacement meter is arranged at the mid-span, 1 m on both sides of the midspan and the support seats at both ends of the girder, respectively, to measure the deflection of the girder at different positions. The number of displacement measuring points is A: 1-5, B: 6-10 and C: 11-15, respectively, according to the number of prefabricated girders from left to right.

3. Analysis of test results

3.1. Test results of B1 and B2
B1 is a monolithic prefabricated I-shaped slab girder. It can be seen from the experimental phenomena that no obvious cracks are found in the girder before the load reached 20 kN. When loads to 20 kN, a transverse crack appears at the corresponding position of the loading point in the middle span of the lower flange of the test girder. Additionally, when the load increases to 25 kN, the cracks penetrate along the bottom of the girder, and rapidly develop to about half of the web height. The load-midspan deflection curve obtained from the test is shown in Figure 3. When the load is less than 25 kN, the load-midspan deflection of the girder is basically linear. During the loading process from 25 kN to 30 kN, the increase of deflection in the middle span of the girder suddenly increases. At this time, obvious cracks appear on the lower flange of the girder, and the overall stiffness of the girder decreases.

B2 is a double-leg girder composed of two prefabricated I-girders A and B. Before the load reaches 30 kN, there is no obvious crack in the girder and it was in elastic working state. Additionally, when the load increases to 35 kN, transverse cracks appear in the middle floor of the right split B span, and extend to the middle of the web along the vertical direction with the floor. The load-mid-span deflection curves of the split girders A and B of B2 under the same load grade are shown in Figure 4. Under different loads, the mid-span deflection of loaded side girder B is obviously larger than that of unloaded side girder A. The girders are in elastic states, and the mid-span deflection of A and B girders increases linearly with the increase of load, and the difference between them increases gradually with the increase of load.

![Figure 3 Load-midspan deflection curve of B1](image)

![Figure 4 Load-midspan deflection curve of B2](image)

3.2. Test results of B3
In case 1, the load is evenly distributed to the loading points of A, B and C of the B3 through two-stage distributed girders. During the loading process, the load increases by 5 kN per stage and the...
maximum load is 50 kN. No obvious cracks are found in the girder during the test, which indicates that the girder is in elastic working state.

In case 2, concentrated load acts on the middle girder of B3 in the middle span of split B, and the loading system is the same as that of case 1. The load-midspan deflection curves of B3 under case 1 and case 2 are shown in Figure 5.

It can be seen from figure 5 that, in case 1, the deflection values of the B3 at each measuring point of split girders A, B and C are basically the same under different load levels. When the load is 50 kN, the mid-span deflection of the girder is 0.45 mm, and the load-midspan deflection of three split girders is linear. In case 2, the deflection of each measuring point of middle split girder B is slightly larger than that of split girder A and C, but the difference is very small. When the load is 50 kN, the mid-span deflection of split girder B is 0.465 mm, and that of split girder A and C is 0.43 mm. In addition, the mid-span deflection of B3 in case 2 is the same as that in case 1, showing a linear relationship. With the increase of load, the difference between them decreases gradually. When the load is greater than 40 kN, the mid-span deflection of each split girder of B3 tends to be the same under the two cases. It can be found that the mechanical performance of B3 girder under case 1 and case 2 is not significantly different, and the lateral connection constraints between the girders of B3 are strong.

![Figure 5 Load-midspan deflection curve of B3 under case 1 and case 2](image-url)

Concentrated load acted on the middle span of B3 girder in case 3, which mainly considers the load performance and lateral distribution of the girder under the combined action of bending and compression under eccentric load. It can be seen from the experimental phenomena that when the load is less than 30 kN, there is no obvious crack in the girder. The load-midspan deflection curve shows a linear relationship, indicating that the girder is in an elastic working state. When the load is 35 kN, a transverse crack occurred in the midspan floor of the split C. The crack develops rapidly to the web, and extends vertically to the middle of the web, and stops loading. The load-midspan deflection curves of B3 under different load levels are shown in Figure 6.
In case 3, the midspan deflection of the splitting C at the loading point is obviously larger than that of the splitting B and A. Under 10 kN, 20 kN and 30 kN loads, the midspan deflections of splitting C are 1.67, 1.75 and 1.67 times of splitting B, 2.5, 2.15 and 2.22 times of splitting A, respectively. When the load is 35 kN load, the midspan deflections of A, B and C were 0.2 mm, 0.28 mm and 0.46 mm, respectively. The load-midspan deflection curves of the splitting parts of the girder show a linear relationship during the loading process, indicating that the girder is in an elastic working state and the midspan deflection difference of adjacent splits increases with the increase of load.

The deflection of the girder can be used to reflect the load condition of each branch, because all the branches of the girder are in elastic working state. According to the transverse distribution of loads, the variation trend of transverse load distribution with load grade is shown in Figure 7. With the increase of vertical load, the proportion of load distributed by each branch of B3 tends to be stable gradually. When the load is greater than 20 kN, the load ratio of branch A, B and C is 0.21:0.3:0.49.

4. Numerical simulation results
The calculation model of B3 is established by MIDAS, as shown in Figure 8. The girder is modeled by solid element, and the steel bar is modeled by link element. According to the principle of equivalence of cross-section area, the calculation model of traditional hollow slab girder with hinged joints is established, as shown in Figure 9. Shallow, middle and deep joints were adopted, and the joint depth is 9 cm, 18 cm and 27 cm, respectively.

4.1. Dynamic characteristic analysis
The analysis results of dynamic characteristics of assembled I-section slab girder and traditional hollow slab girders with three different hinge joints are shown in Table 2.
Table. 2 Comparison of dynamic characteristics between I-girder and hollow plate girder

| Order | Frequency (Hz) | Mode of vibration |
|-------|----------------|-------------------|
|       | Assembled I-girder | Deep-hinge hollow plate girder | Middle-hinge hollow plate girder | Shallow-hinge hollow plate girder |
| 1     | 39.39           | 39.84             | 39.99                           | 40.09                         | Vertical bending first order |
| 2     | 76.99           | 81.86             | 75.34                           | 73.76                         | Torsional first order       |
| 3     | 100.61          | 101.07            | 101.27                          | 101.95                        | Vertical bending second order |
| 4     | 129.32          | 131.33            | 120.16                          | 119.05                        | Transverse bending first order |

The first four modes of the four girders are the same, and the corresponding frequencies of the first modes are basically the same, which shows that the overall vertical stiffness of the four girders is basically the same. The corresponding frequencies of torsional first-order mode shapes are 81.86 Hz for deep-hinged hollow slabs, 76.99 Hz for assembled I-girders, and 75.34 Hz for medium-hinged hollow slabs and 73.76 Hz for shallow-hinged hollow slabs, respectively. It is indicated that the torsional stiffness of deep hinge hollow slab, assembled I-girder, middle hinge hollow slab and shallow hinge hollow slab are in turn from large to small. However, the first-order torsional mode participation mass of the assembled I-girder structure is 0.07%, which is less than other three girders. It shows that the torsional deformation of the I-girder structure is smaller, and the overall torsional stiffness is relatively larger.

4.2. Calculation results of displacement
The displacement of the traditional hollow plate girder with shallow, middle and deep hinge joints under load is numerically analyzed. In order to compare with the test results, the same loading mode as B3 is adopted. The load is 10 kN at each loading point, 30 kN at the mid-span of side girder B and C. The mid-span section deflection of traditional hollow slab girder models with shallow, middle and deep hinged joints under corresponding loads is calculated, and compared with the experimental data of B3, as shown in Figure 10-12.

![Figure 10](image_url)
Figure. 11 Mid-span section deflection in case2

Figure. 12 Mid-span section deflection in case3

Under three cases, the mid-span deflection of deep-hinge hollow slab is obviously smaller than that of shallow- and middle-hinge hollow slab, which is consistent with the actual situation. While the mid-span deflection test values of assembled I-girder structure are less than that of traditional hollow slab structure, which indicates that the overall stiffness of assembled I-girder structure is much higher than that of traditional hinged jointed hollow slab structure. In addition, the transverse load distribution of assembled I-girder is more uniform than other three hollow plate girders, and the overall performance of proposed girder is better.

4.3. Calculation results of stress

The shear stress of the joints is the main index affecting the fatigue performance of structures [16]. The maximum shear stress at the transverse joints of four different types of girders under three-girder loading, middle-girder loading and side-girder loading is listed in Table 3.

Table 3 the maximum shear stress of the joint

| Case Type                        | Maximum shear stress at midspan joint (kPa) |
|----------------------------------|---------------------------------------------|
|                                  | 10 kN on three girders | 30kN on mid-girder | 30kN on side-girder |
| Prefabricated I-section girder   | 487                         | 648               | 733                |
| Deep-hinge hollow plate girder   | 488                         | 987.6             | 1140.3             |
| Middle-hinge hollow plate girder | 538.2                        | 1004.9            | 1129.6             |
| Shallow-hinge hollow plate girder| 549.3                        | 929.1             | 1025.7             |
Under these three loading conditions, the maximum shear stress of the connection part of the I-section girder structure is less than that of the traditional hollow slab girders. Thus, under the same load conditions, the stress amplitude of the joint of the assembled I-section girder structure is smaller, and the fatigue resistance of the assembled I-section girder structure is better under the long-term reciprocating action of vehicle load.

5. Conclusion
(1) The assembled I-section slab girder proposed in this paper has higher overall flexural and torsional stiffness than the traditional hollow slab girder, better overall performance and more uniform load distribution among the transverse segments.
(2) Under the same load conditions, the shear stress amplitude of the connection part of the assembled I-section slab girder is smaller, and the fatigue resistance of the assembled I-section slab girder is better than that of the traditional hollow slab girder.
(3) Only one support is needed at one end of each girder in the construction process, which effectively solves the problem that the traditional hollow slab girder is prone to support void. The prefabricated girders are connected reliably by steel bars stretched out from the flange plate. The wet joint has a large working surface, and the construction is relatively simple and the quality is easy to control. It avoids the problem that the quality of the traditional hollow slab structure is difficult to guarantee due to the semi-concealed construction of the hinge joints. It has broad application prospects.

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