International Journal of Robotics and Automation, Vol. 36, 2021

Special Issue: Automatic Detection and Assessment of Bridge Structures

SAFETY ANALYSIS OF HOLLOW PLATE GIRDER BRIDGE BASED ON ROUTINE DETECTION INDEXES

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Abstract

Hinge joints, cracks, and permanent deformation have a significant influence on the safety of the hollow plate girder bridges. The effects of these factors on the safety performance of hollow plate girder bridges with different spans were analysed with the help of the MIDAS/finite element analysis (FEA) numerical simulation platform. First, a multilevel damage finite element model of the different damage forms of hollow plate girder bridges with a typical span was established, and the influence of the joint damage on the safety performance of the hollow plate girder bridges was analysed. Second, taking the height of the hinge joints as the research parameter, nonlinear FEA was carried out under monotonic loading and repeated loading, and the influence of different crack states on the internal force and deformation of the hollow plate girder bridges was analysed. Finally, the simplified calculation formula of the permanent deformation limit of hollow plate girder bridges was established based on the premise of the ultimate strain of the concrete in the compressive zone of the main girder. The research results can provide a reference for the safety evaluation of hollow plate girder bridges.

Key Words

Hollow plate, safety performance, hinge joints failure, height of hinge joints, permanent deformation

1. Introduction

Assembled reinforced concrete (RC) hollow plate girder bridges are widely used in highway bridge construction in China because of their numerous advantages, such as their simple structure, factory prefabrication, convenient construction, and low cost [1]. According to some studies, medium-to-small highway bridges with spans under 20 m in China mostly have a prefabricated hollow slab structure [2]. However, with the increase of the service period, damage occurs to the hollow plate girder bridges, including hinge joint failures, cracks, and permanent deformation, which exert a significant influence on the safety of the hollow plate girder bridges [3].

Hinge joint failure has a severe impact on the safety of prefabricated hollow slab bridges and the development of this type of bridge. Therefore, researchers in China have conducted extensive research on hinge joint strain and failure mechanisms. Ye *et al.* [4] designed a test for hinge joint shear performance and proposed a formula to calculate the hinge joint shear strength and bearing capability. Zhong [5] and Wang *et al.* [6] conducted model and experimental studies on prefabricated hollow slabs with various forms of hinge joint connections and hinge joint reinforcements. Leng *et al.* [7] utilized finite element analysis (FEA) on the crack length of single-sided and two-sided hinge joints and obtained the reasonable critical hinge joint crack length. Wei *et al.* [8], [9] did research on the performance and durability of the hinge joints and divided the cracking degree into three types: deep, moderate, and shallow. Yuan *et al.* [10] and Tang *et al.* [11] conducted model and experimental studies on prefabricated hollow slabs with various forms of hinge joint connections and hinge joint reinforcements. The following results were found: (1) as the hinge joint height increases, the horizontal connection performance of the adjacent slabs improves accordingly, (2) the fatigue load is a major factor for shallow hinge joint failure, (3) compared with the hinge joint without a rebar, adding a cross rebar and door rebar at the hinge joint improves the load transmission capability of the hinge joint, and (4) the working performance is influenced by the reinforcement ratio, form, concrete strength ratio, and (5) the coordinated working performance of deep hinge joint is better than that of shallow and middle hinge joint, but the durability of the former is worse than that of the latter.

Fracture development and bearing capacity are also important for prefabricated hollow slab bridges. Wang *et al.* [12] did research on the residual bearing capacity of the hollow plate with longitudinal cracks in the web plate. Yi *et al.* [13] performed tests to investigate the cracking

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Recommended by Dr. Jingzhou Xin
(DOI: 10.2316/J.2021.206-0532)

load, failure mode, and force transmission performance of the hollow slab girder and shallow hinge joint under the vehicle load during the demolition and reconstruction of an old bridge. Li *et al.* [14] proposed a deep learning CNN model with 11 trainable hidden layers to automatically extract and classify the bridge damage represented by the continuous deflection of bridge. The model accuracy could reach 96.9% and illustrated a reasonable ability to distinguish damage from structurally symmetrical locations.

Many scholars have researched hollow plate damage identification and its influencing factors. However, researches on the influences on hollow plate girder bridge safety, such as the multilevel hinge joint damage, the height of the crack, and permanent deformation, are rarely reported. We analysed the factors affecting the safety of hollow plate girder bridges.

First, the validity of the finite element simulations of the hinge joints was verified by a comparison between the experimental results and numerical simulations. We evaluated a 10-m long typical span of a hollow plate girder bridge on the bridge's safety performance with three forms of damage – single-hinge joint damage, adjacent hinge joint damage, and side hinge joint damage – at five degrees of damage (0%, 20%, 40%, 60%, and 80%). Second, by taking the height of the hinge joints as the research parameters, the nonlinear FEA was carried out under monotonic loading and repeated loading, and the influence of $0.3h$–$0.8h$ cracks on the internal force and deformation of hollow plate girder bridges was analysed. Finally, the validity of the simplified calculation formula of the permanent deformation limit of the hollow plate girder bridge was verified by the effect of the permanent deformation caused by the loss of the prestress in the hollow plate bridge, which was simulated by the finite element model. The research results provide a reference for the safety evaluation of hollow plate girder bridges.

2. Hinge Joint Failure

The sway bracing of the hollow plate is connected by the hinge joint. When the hinge joint damage reaches a certain degree, it can cause the "stress on a single slab" phenomenon, which can severely weaken the lateral rigidity of the hollow plate. We verified the validity of the FEA method through experiments by taking the transverse distribution coefficient of the deflection as the research object. Then, the hinge joint damage of the hollow plate girder bridges was established using the finite element model, and the transverse distribution coefficients of the deflection of the multilevel damage were compared to examine the safety performance assessment of the hollow plate girder.

2.1 Comparison and Analysis of the Transverse Distribution Coefficient at the Midspan Section

2.1.1 Principle of the Transverse Distribution Coefficient of Deflection

The sum of the midspan deflections of all the plate beams of a hollow plate beam is the total deflection, whereas the ratio of the midspan deflection of each plate beam to the total deflection is the deflection transversal distribution coefficient: the smoother the coefficient along the transverse direction is, the better the integrity of the hollow plate beam (Fig. 1).

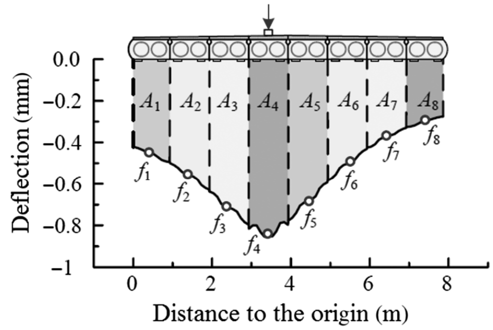


Figure 1. Determining values for the calculation of the transverse distribution coefficient of deflection: the transverse distribution coefficient of deflection under a certain load condition is $\eta_i = f_i/\sum_{i=1}^{n} f_i$.

Figure 2. Solid test model.

Figure 3. Deflection measurement.

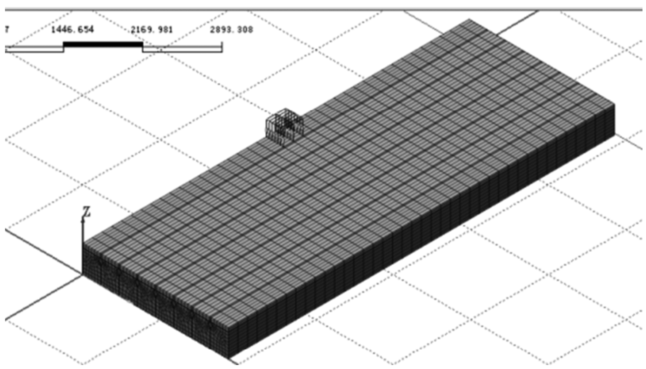


Figure 4. Finite element model.

2.1.2 Test

We used a 10-m-long span of an RC hollow plate girder bridge for this research. The geometric similarity constant of 1/2 of the model was chosen to carry out the scale test of the structure with a C30 grade of concrete and I Steel Bar, including 4 $\phi 16$ steel bars in the tensile zone and 2 $\phi 18$ constructional steel bars. The model is shown in Figs. 2 and 3.

The deflection of the bottom of each plate with section L/2 was measured in the test of the RC hollow plate scale model when 3 t of a concentrated load was placed on section L/2 of plates 1–4.

2.1.3 Finite Element Analysis

FEA was used to establish the numerical simulation model of the test beam, as shown in Fig. 4.

Similarly, when a 3-t concentrated load was placed on the L/2 section in plates 1–4, the bottom deflection of all of the plates in section L/2 in the finite element model of the hollow plate was obtained.

The transverse load distribution coefficient obtained through the finite element simulation and that obtained by the test and theoretical calculation (using the hinge-jointed plate method) are compared in Fig. 5.

Figure 5 shows that the finite element calculation results are close to the experimental ones, as well as the transverse distribution coefficient calculated by the hinge-jointed plate method, which verifies the reliability of the finite element model.

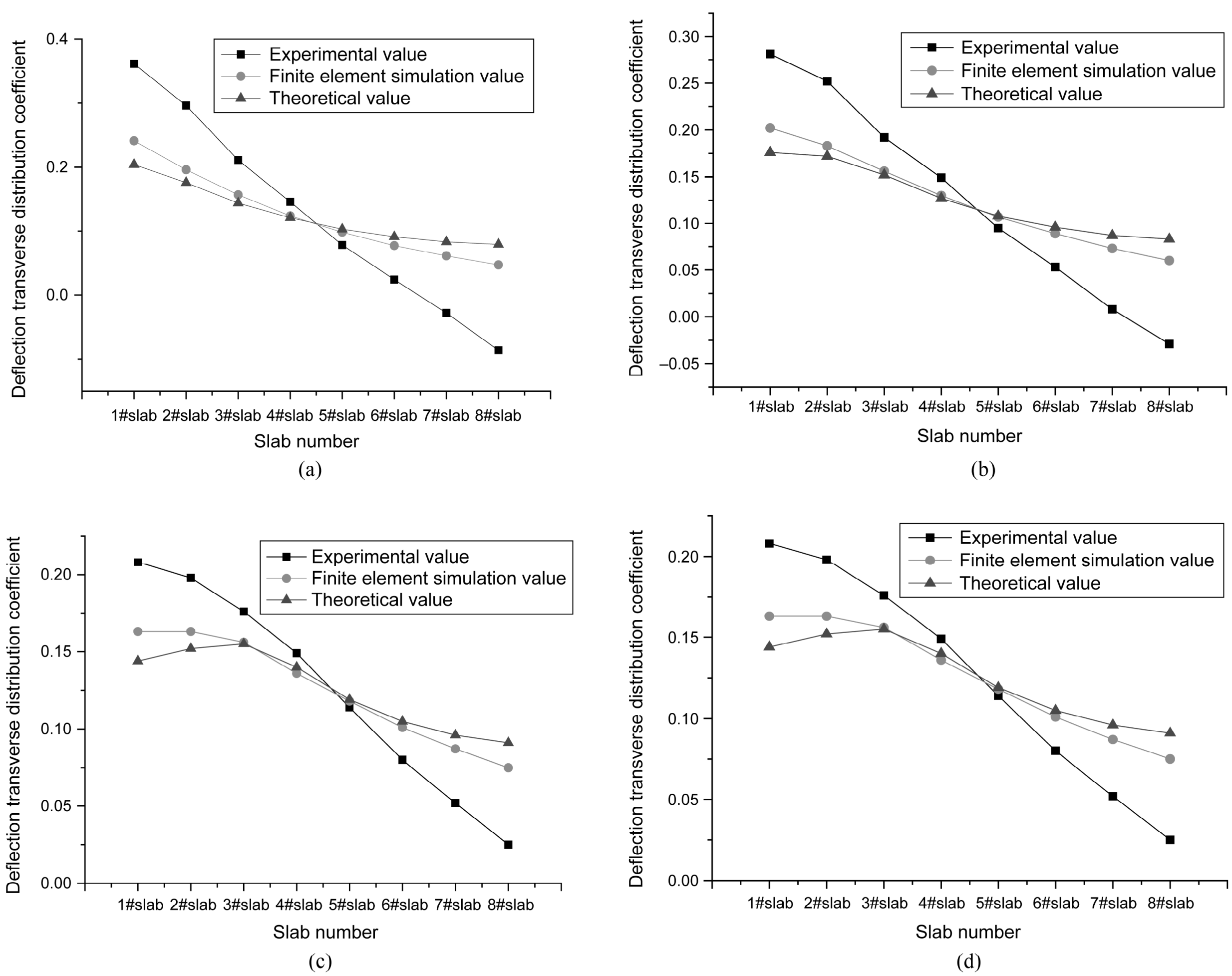


Figure 5. Transverse load distribution coefficient of each plate: (a) load applied to the midspan of plate 1; (b) load applied to the midspan of plate 2; (c) load applied to the midspan of plate 3; and (d) load applied to the midspan of plate 4.

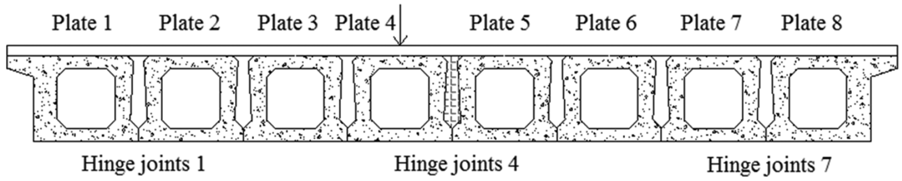


Figure 6. Schematic diagram of hinge joint 4 damage.

Table 1
The Results of the Transverse Distribution Coefficient Test for Single-Hinge Joint Damage

Plate Number	Absolute Value					Relative Value (Compared with Intact Value) (%)			
	20%	40%	60%	80%	0	20	40	60	80
1	0.128	0.149	0.162	0.184	0.127	1	17	27	44
2	0.131	0.153	0.176	0.196	0.129	1	18	36	52
3	0.133	0.158	0.191	0.265	0.132	1	20	45	101
4	0.136	0.169	0.210	0.248	0.133	2	27	58	86
5	0.127	0.106	0.074	0.037	0.129	−1	−18	−42	−72
6	0.121	0.094	0.069	0.029	0.122	−1	−23	−44	−76
7	0.114	0.088	0.061	0.026	0.116	−2	−24	−48	−78
8	0.109	0.082	0.057	0.017	0.111	−2	−26	−49	−85

2.2 Damage Model Analysis of Hinge Joint of the 10-m-Span Reinforced Concrete Hollow Plate Girder Bridge

2.2.1 Model Establishment and Simulation of the Hinge Joint Damage

The prototype was an RC simply supported hollow plate beam bridge with a span of 10 m, which was 8.5 m wide and consisted of eight hollow plates connected by hinge joints. C40 concrete was used in the plate beam and hinge joints. The hinge joint between the side plate and the adjacent medium plate was defined as hinge joint 1, and hinge joints 1–7 were counted from the left side to the right side of the cross-section of the bridge deck. By changing the number of the solid elements at the hinge joint or the material properties of the hinge joint element, the hinge joint damage of the hollow plate girder bridges can be simulated by MIDAS/FEA. The back calculation of the degree of hinge joints damage was made using the trial calculation. We assumed the hinge joint was nondestructive, and so the load force was distributed through the hinge joints in the transverse direction under actions of the constant load. The stress σ_1 of the middle point of the adjacent hollow plate floor was extracted. Then, the number of the solid element and material properties of the hinge joints were changed to simulate the hinge joints of the injury, and the stress σ_2 was extracted in the same condition. The value of $1-\sigma_1/\sigma_2$ was calculated as a percentage of the degree of the damage of the hinge joints.

2.2.2 Result

2.2.2.1 Analysis of the Hinge Joint Damage and the Analysis of the Single-Hinge Joint Damage

We used the middle hinge joint (hinge joint 4) as the study object (as shown in Fig. 6), and a 300-kN vertical concentrated load was used on the section at the midspan of plate 4 to study the variation of the transverse load distribution coefficient of all of the plate beams subjected to damage of different degrees.

The vertical concentrated loads acting on the midspan of plate 4 and hinge joint 4 were subjected to damage of different degrees. The calculated values of the transverse load distribution coefficient in the section at midspan of the bottom edge of plate beams are shown in Table 1.

Table 1 shows that when hinge joint 4 is damaged, the loads act on beam 4 with the weakening of the transverse connection. The load shared by beam 4 (loading plate) also increases significantly, and the transverse distribution coefficient increases from 0.133 of the intact state to 0.21 of 60% of the damage rate, and then to 0.248 of 80% of the damage rate. After the hinge joint damage rate reaches 60%, the transverse distribution coefficient of plate 4 increases sharply, showing the stress on a single slab.

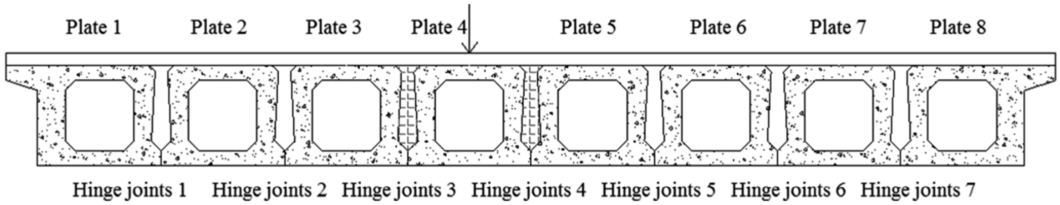


Figure 7. Schematic diagram of two adjacent hinge joints' damage.

Table 2
The Result of Transverse Distribution Coefficient of the Double-Hinge Joint Damage

Plate Number	Absolute Value					Relative Value (Compared with Intact Value) (%)			
	20%	40%	60%	80%	0	20	40	60	80
1	0.125	0.112	0.112	0.092	0.127	−2	−12	−12	−28
2	0.128	0.117	0.117	0.096	0.129	−1	−10	−10	−26
3	0.132	0.123	0.119	0.103	0.132	0	−7	−10	−22
4	0.142	0.221	0.313	0.448	0.133	7	66	135	237
5	0.129	0.118	0.118	0.107	0.129	0	−8	−8	−17
6	0.121	0.110	0.090	0.081	0.122	−1	−10	−26	−34
7	0.115	0.103	0.071	0.046	0.116	−1	−11	−39	−60
8	0.109	0.097	0.061	0.028	0.111	−2	−13	−45	−75

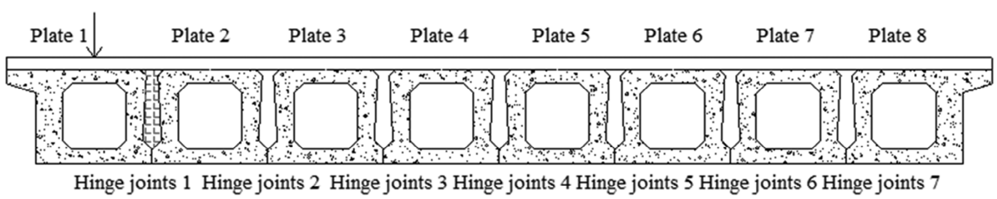


Figure 8. Schematic diagram of the side hinge joint damage.

2.2.2.2 Analysis of Two Adjacent Hinge Joints' Damage

We evaluated the change of the transverse distribution coefficient of each plate girder subjected to damage of different degrees where the two sides of the hinge joints (hinge joint 3, hinge joint 4) of a medium plate (plate 4) were damaged at the same time (as shown in Fig. 7). A 300-kN vertical concentrated load acted on the cross-section of plate 4. The calculated values of the transverse distribution coefficient of the cross-section of the plate girder are shown in Table 2.

Table 2 shows that when hinge joint 3 and joint 4 have damage of 20% at the same time, the influence on the transverse distribution coefficient is not serious (of which the maximum is about 7%). However, when the damage rate is more than 40%, the increase rate of the transverse distribution coefficient reaches 66% and the trend of the stress on a single slab is significant.

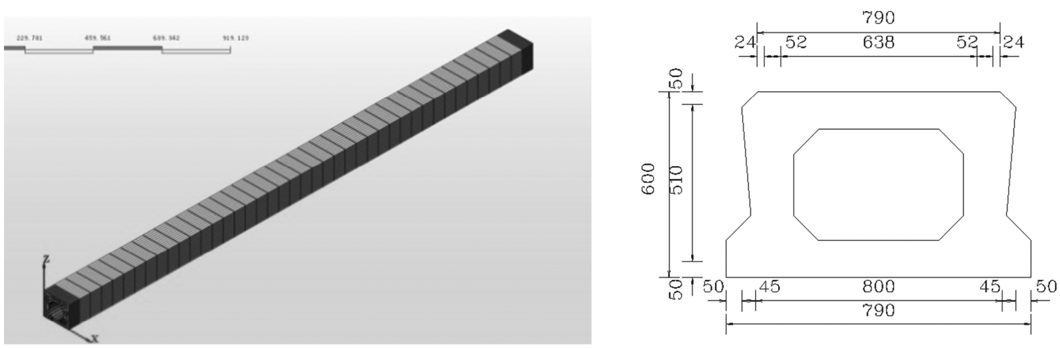
2.2.2.3 Analysis of the Side Hinge Joint Damage

To study the changes of the transverse distribution coefficient of each plate girder for different degrees of damage, the side hinge joint (hinge joint 1) was the research object (as shown in Fig. 8) and a 300-kN vertical concentrated load acted on the cross-section of plate 1. The theoretical calculation of the transverse distribution coefficient of the cross-section of the lower edge of the plate girder is shown in Table 3.

The results show that there is little effect on the transverse distribution coefficient of each beam when the load acted on beam 1 and the rate of hinge joint 1's damage is 20%. When the damage rate reaches more than 40%, the rate of the transverse distribution coefficient reaches 57%, and the stress on a single slab is significant. Because plate 1 is the only one-sided hinge joint, it can be understood as the damage to the joints adjacent to board 1, and the result of the assessment is consistent with the result of

Table 3
The Result of Transverse Distribution Coefficient of the Side Hinge Joints Damage

	Absolute Value					Relative Value (Compared with Intact Value) (%)			
Plate Number	20%	40%	60%	80%	0	20	40	60	80
1	0.213	0.299	0.405	0.546	0.191	12	57	112	186
2	0.165	0.158	0.143	0.120	0.165	0	−4	−13	−27
3	0.143	0.122	0.110	0.103	0.145	−2	−16	−24	−29
4	0.121	0.104	0.091	0.040	0.126	−4	−17	−28	−68
5	0.109	0.092	0.078	0.067	0.110	−1	−16	−29	−40
6	0.094	0.079	0.060	0.051	0.098	−3	−19	−38	−48
7	0.083	0.076	0.059	0.046	0.087	−5	−12	−32	−47
8	0.072	0.069	0.054	0.028	0.078	−8	−12	−31	−64



(a)
(b)

Figure 9. Solid model of a single beam: (a) finite element model and (b) cross section (mm).

the joint damage. Generally, as the damage to a single-hinge joint of the RC hollow plate beam bridge increases, the transverse distribution coefficient of the loading plate increases significantly, demonstrating a trend of first a slow and then a rapid increase. When the hinge joint damage reaches 60%, the stress on a single slab is clear. The safety of the hollow plate girder bridge is affected when the hinge joints damage reaches more than 60%. Along with the increase of the damage degree of the adjacent hinge joints, the transverse distribution coefficient of the loading plate increases slowly at first and then fast afterwards. When the damage reaches 40%, the stress on a single slab becomes apparent. When the damage degree of the adjacent hinge joints reaches 40%, the state of the hollow plate girder bridge can be considered stress on a single slab.

3. Cracks

The *Specification for Highway Bridge and Culvert Maintenance* (JTG H11-2004) [15] has strict requirements for crack control, but these merely refer to the control of the width limit. As hollow plate girder bridges usually operate with cracks, the distributed crack model of the finite element model is adopted to simulate cracks, and the influence of the height of cracks on bridge safety performance has been analysed [16].

3.1 Modelling

An RC hollow plate girder bridge with a span of 10 m was created using a finite element model, and C40 concrete was used in the plate beam and hinge joints. Asphalt concrete with a thickness of 3 cm was used in the upper layer of the bridge deck pavement, and C40 concrete with a thickness of 6 cm was utilized in the lower layer. Eight HRB335 rebars with a diameter of 32 mm were used, of which the area was 6,430.72 mm^2. The finite element model of the monolithic hollow plate beam is shown in Fig. 9.

Values of $q_k = 10.5$ kN/m and $p_k = 200$ kN were calculated using the linear interpolation. Defining a lane loading of highway level I as the reference load Q, the live load acted on the main beam at the same time. k is the load factor, $k = \zeta \times \eta$, and ζ is the correction coefficient of live load under heavy load or the overload. η is the transverse load distribution coefficient.

Table 4
Change Value of the Deflection at the Midspan under Different Loads

Load factor k	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Midspan deflection (mm)	3.1	4	5.2	6.9	8.9	11.1	13.6	15.2

Table 5
Development of the Cracks of the Single Girder under Different Loads

Load factor k	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
The height of the cracks	$0.12h$	$0.3h$	$0.4h$	$0.5h$	$0.56h$	$0.6h$	$0.7h$	$0.8h$

3.2 Results

3.2.1 Analysis of the Results under Monotonic Loading

Linear loading occurs when stress is placed on the main girder gradually until the girder is damaged. The deflection, concrete stress, and other change rules, as well as the generation and development of cracks in the hollow plate main girder under all of the levels of loads were evaluated.

3.2.1.1 Midspan Deflection

Deflection is an important index reflecting the stiffness of structures, and values of the deflection under different loads were calculated using the finite element model, which is shown in Table 4.

According to the *Code for the Design of Reinforced Prestressed Concrete Highway Bridge* (JTG D62-2012) [17], the deflection of the bending members in the service stage should consider the influence of the long-term effects of the load. When the strength of the concrete is below 40 MPa, the long-term effect coefficient $\eta_\theta = 1.6$.

The deflection limit of the main girder is

$$[f] = \frac{1}{h_q} \times \frac{L}{600} = \frac{1}{1.6} \times \frac{10,000}{600} = 10.4 \text{ mm}$$

When the load factor$k \geq 0.8$, the deflection of the cross-section of the main girder $f = 11.1$ mm, which exceeds the limit value specified.

3.2.1.2 Development of Cracks

The mechanical behaviour of a beam is determined through the development of the cracks in the hollow plate girder bridge. The development of the cracks in the hollow plate girder bridges under different loads determined using the finite element model is shown in Table 5.

According to the previous research, when $k = 0.8$ and the height of the crack is 0.6 times higher than the beam, the midspan deflection is 11.1 mm, which is greater than the limit value $[f]$ in the specification, namely 10.4 mm. According to the derivation therefore when k is 0.8 and the height of the crack reaches $0.6h$, the cross-section of the hollow plate beam is close to damaged.

Table 6
The Load and the Midspan Deflection for Different Heights of the Crack (mm)

	The Height of the Crack					
k	$0.3h$	$0.4h$	$0.5h$	$0.6h$	$0.7h$	$0.8h$
0.4	4	4.4	5.1	6.4	7.1	8.3
0.5	–	5.2	6.1	7.7	8.5	9.9
0.6	–	–	6.9	8.9	9.8	11.5
0.8	–	–	–	11.1	12.5	14.6
0.9	–	–	–	–	13.6	16.1
1.0	–	–	–	–	–	18.9

3.2.2 Analysis of the Results under Cyclic Loading

To study the change of the performance of the RC hollow plate girder bridge before and after the cracking, cyclic loads were applied to the main girder to promote the cracking development, and the changing rules of the deflection of the main girder and concrete stress under different crack development degree were studied.

3.2.2.1 Midspan Deflection

The relationship between the load and the midspan deflection for different heights of the crack is shown in Table 6.

Table 6 shows that when $k \leq 0.6$ and the height of the crack of the single hollow plate girder crack is $0h$–$0.6h$, the midspan deflection is in accord with the regulations and stipulations, and when $k \geq 0.8$ and the height of the crack of the single hollow plate girder crack is greater than or equal to $0.6h$, the midspan deflection exceeds the limit values specified.

3.2.2.2 Compressive Stress of the Upper Margin of the Midspan Concrete

The maximum compressive stress of the load and the upper margin of the midspan concrete for different heights of the crack are shown in Table 7.

Table 7 shows that when $k \leq 0.6$ and the height of the crack of the single hollow plate girder is $0h$–$0.6h$, the compressive stress of the upper margin of the midspan concrete is in accord with regulation, and when $k \geq k8$ and the height of the crack of the single hollow plate girder crack is greater than or equal to $0.6h$, the compressive stress of the upper margin of the midspan concrete exceeds the limit values specified.

To summarize, the results of the tests of the safety performance of the main girder of the RC hollow plate girder bridge according to the development degree of the crack are as follows:

1. When $k \leq 0.6$, and the height of the crack of the single hollow plate girder crack is $0h$–$0.6h$, the main girder is in the safe state.

Table 7
The Stress of the Upper Margin of the Midspan Section with Different Heights of the Crack (MPa)

	The Height of the Crack					
k	$0.3h$	$0.4h$	$0.5h$	$0.6h$	$0.7h$	$0.8h$
0.4	4.5	8.9	9.5	10.4	10.7	11.1
0.5	–	10.1	11.8	12.8	13.2	13.7
0.6	–	–	12.0	15.3	15.7	16.1
0.8	–	–	–	19.9	20.7	21.4
0.9	–	–	–	–	22.1	23.6
1.0	–	–	–	–	–	28.9

2. When $k \geq 0.8$, and the height of the crack of the single hollow plate girder crack is greater than or equal to $0.6h$, the midspan deflection and midspan concrete stress exceed the limit values of the specification. If there is damage on the partial concrete of the upper margin of the midspan of the main girder, the bridge is in a dangerous state.

4. Permanent Deformation

The current national codes indicate that the deflection of a bridge under a live load should not exceed L/600 in the serviceability limit state. However, the permanent deformation limit under the long-term load is not regulated. When the main girder generates the downward deflection due to concrete shrinkage and creep and the loss of the prestress, the strain of the concrete in the compressive zone will increase significantly and the bearing capacity of the bridge will weaken considerably. Therefore, it is of practical significance to develop a kind of limit formula of permanent deformation theory to evaluate the safety of the hollow plate bridges [18].

4.1 Theoretical Limit to Permanent Deformation of a Hollow Plate Bridge

After the bending deformation of hollow plate girder bridge occurs, all of the cross-sections in the pure bending section rotate around the neutral axle and the section remains plane. Then the curvature of the deflection curve can be obtained according to the material mechanics:

$$\phi = \frac{1}{\rho} = \frac{d^2y}{dx^2} = \frac{M}{B} \tag{1}$$

where B is section area, M is bending moment, and ρ is the curvature radius of the deformation curve of the section.

On the basis of the premise of the strain of the concrete in compression zone of the main girder reaching ε_u, a simple limit formula of the permanent deformation of the RC hollow plate girder bridge can be established through the analysis of the determination factor. The general expression of the relationship between the deflection and the curvature of the hollow plate girder bridge can be written as follows:

$$f = C \times \phi \times l^2 \tag{2}$$

where f is deflection, C is coefficient associated with the shape of the deflection curve, and l is the calculated span of the bridge. The limit formula of the permanent deformation of the hollow plate girder bridge was established through the analysis of the values of the parameters.

4.1.1 Value of C

The possible deflection can be in the shape of a parabola, a circular curve, or a deflection curve for hollow plate girder bridges. The parabola and the circle curve are quadratic curves, which can be calculated by the standard equation in analytic geometry. The deflection curve is derived from the mechanics of materials, and the deflection curve of the hollow plate girder bridge under a uniform load is smooth and continuous. The line type of deflection curve is more in line with the deformation characteristics of concrete hollow plate girder bridges, so the deflection curve was adopted in the analysis calculation ($\beta = 10$ and $C = 1/10$).

4.1.2 Value of ϕ

Curvature ϕ is the ratio of the compressive strain of the concrete in the compressed edge with the distance from the neutral axis to the compressed edge of hollow plate girder bridges:

$$\phi = \frac{\varepsilon}{x} \tag{3}$$

When ε reaches ε_u, which is the ultimate compressive strain of concrete compressed edge, it can be considered that further downward deflection will not occur in the midspan of the bridge, and the value of ε_u is 0.003. The formula of the height of the compression zone is $x_c = \xi_{jp} h_0$, and ξ_{jp} is the height-limit coefficient of concrete compression zone: $x_c = \xi_{jp} h_0 = h/2$. The following formula can be obtained:

$$\phi = \frac{\varepsilon_u}{x_u} = \frac{0.003}{h/2} = \frac{0.006}{h} \tag{4}$$

According to the analysis of the parameters, when the concrete compressive strain reaches the ultimate compressive strain, the deflection value of the main girder is shown in (5):

$$f = C \times \phi \times l^2 = \frac{1}{10} \times \frac{0.006}{h} \times l^2 = 0.0006 l^2/h \tag{5}$$

The previous formula considers the effect of a live load, but only the permanent deformation of the hollow plate girder bridges is considered in this article, the dead load coefficient C_H is discussed using C_H: dead load/total load, and the coefficient considering the section shape C_m should be also considered. $C_m = 1.5$ for the hollow plate

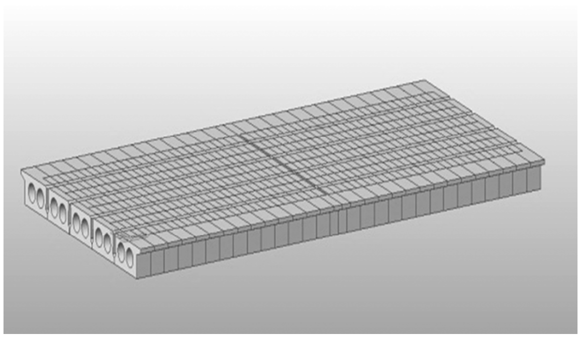


Figure 10. Finite model of the prestressed hollow plate girder bridge.

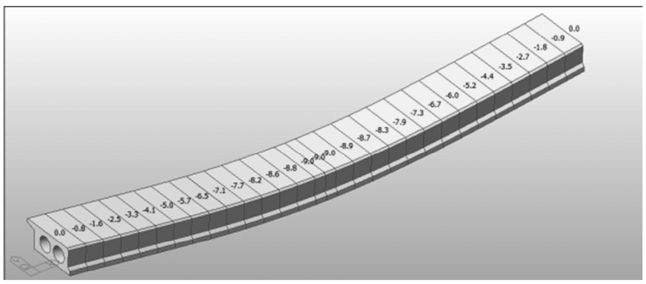


Figure 11. Deformation caused by the prestress loss.

girder bridges. The permanent deformation limit formula was obtained:

$$[f] = 0.0006\frac{1}{n_f}C_m C_H \times l^2/h \qquad (6)$$

where n_f is the safety factor. $n_f = 6.0$, and so the final theoretical limit formula of permanent deformation of hollow plate girder bridge was obtained:

$$[f] = 0.00015 \times C_H \times l^2/h \qquad (7)$$

4.2 Model Building and Result Analysis of the Prestressed Hollow Plate Girder Bridge

The finite element model of the prestressed hollow plate girder bridge was established by MIDAS. The span was 13 m and the height of the beam was 1.2 m (Fig. 10).

1. The prestress loss reaches 40% and causes deformation. The deformation caused by the prestress loss is shown in Fig. 11. The maximum deflection is 9 mm, the bearing capacity meets the requirements, and the calculating bending moment is far less than the bearing capacity at the bending moment and a large surplus of bearing capacity is available.
2. When the prestress loss is 50% and the permanent deformation is 11.9 mm, its bearing capacity meets the requirements, and the calculated bending moment is close to the bearing capacity at the bending moment. When the prestress loss is 50%, 11.9 mm of the permanent deformation is the permanent deformation limit.
3. When the prestress loss is 60% and the permanent deformation reaches 14.8 mm, 23.8% of the calculated value of the unit moment is greater than the bearing capacity of the bending moment, and the corresponding bearing capacity cannot meet the requirements. The hollow plate girder bridge is in a dangerous condition at that time.

The further comparison and analysis of the theoretical limit values and results of the finite element simulation is given by

$$[f] = 0.00015 \times C_H \times l^2/h = 0.00015 \times \frac{718}{718+536} \times 13^2/1.2 = 0.012\text{m}$$

The permanent deformation limit calculated with the formula is 12 mm, and the permanent deformation limit through the analysis of finite element is 11.9 mm. The permanent deformation of the prestressed RC hollow plate girder bridge with a span of 13 m calculated by the limit formula [Equation (l)] is essentially consistent with the simulation results of the finite element model. The theoretical limit formula of the permanent deformation can be used to evaluate the safety performance of a hollow plate bridge.

5. Conclusion

Factors such as the hinge joints, cracks, and permanent deformation have a significant influence on the safety of the hollow plate girder bridges. In this article, the safety performance of hollow plate girder bridges with different spans was analysed with the help of the MIDAS/FEA numerical simulation platform. The main conclusions of this study can be summarized as follows:

- When the single-hinge joint damage exceeds 60%, the hollow plate girder bridge is considered to be in the state of stress on a single slab. When the adjacent hinge joints' damage degree reaches 40%, the stress on a single slab state should be taken into consideration as it affects the safety of the main girder.
- When $k \leq 0.6$ and the height of the crack is $0h$–$0.6h$ in the single RC hollow plate girder, the main girder is in a safe condition. When the height of the crack of the RC single hollow plate girder is greater than or equal to $0.6h$, the bridge is in a dangerous state.
- The formula for calculating the theoretical limit of permanent deformation of $[f] = 0.00015 \times C_H \times l^2/h$ is proposed here. The formula is valid and can be used to evaluate the safety performance of a hollow plate girder bridge.

Acknowledgement

This work was supported by the Science and Technology Planning Project of Yunnan Province of China (2017IB025).

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