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Study on the Hinge-joined Plate Method

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ABSTRACT: In order to verify and perfect the theory of hinge-joined plate method, and make it serve the bridge design better, this paper was written based on an actual bridge, and the ANSYS finite element model was established. Compared the hinge-joined plate method results with the analysis results and through the investigation and data analysis, it could be found that the assumption that the hinge-joined plate theory for the board lateral force transmission is reasonable, but the assuming hinge joints that only withstand shear stress and just have the shear checking is unreasonable. At the same time, this paper also proved that the strength reduction getting from the old and new concrete interface should be taken into account when using the hinge-joined plate method to calculate the transverse distribution coefficient and the effects on overall stiffness that the joint depth and thickness of deck pavement to the beam bridge.

Keywords: transverse distribution coefficient; hinge-joined plate method; finite element method; new-old concrete adhesive interface; the simply supported hollow slab bridge

1 INTRODUCTION

The assembly type hollow plate girder bridge has advantages of simple structure and convenient construction. Usually, small and medium-sized girder bridges are composed of the beam-slab bridge or some main girders with transverse connected girder bridge by deck slab. Based on the action of loading, the horizontal contact strengths are different and the main girder is working in different levels, which resulted in beam-slabs which are unevenly stressed and suddenly changed. The strength of horizontal contacted beam-slabs is represented by the transverse distribution coefficient. The followings are some common calculation methods for the transverse distribution coefficient: the lever principle method, the transverse hinge-joined plate method, the transverse stiffness connection method and the compared orthotropic plate method[i]. Different calculation methods are with and applied to different bridge structure. For example, the hinge-joined plate method is mainly suitable for the design of assembly type hollow plate girder bridge which is connected with the cast-in-situ concrete rabbet joint. The transverse connection among plates is weak, and veneer force phenomenon occurs often. So that the calculation of transverse distribution coefficient is an absolutely necessary link to the design. The hinge-joined plate method can be used to simplify the calculation by simplifying a space problem to a plane problem. However, people are still exploring its correctness. In this regard, this paper based on some existing bridge model will use the finite element analysis software to compare the results of finite element analysis and articulated the slab method calculation, aiming to explore the validity of the hinge-joined plate method theory and achieve its further perfection.

2 HINGE-JOINED PLATE METHOD [2][3][4][5]

The hinge-joined plate girder method theory is that the concrete hinged joint is connected with the hollow plate girder bridges and transform the internal force. The theory makes the following assumptions to calculate the transverse distribution coefficient:

(1) The joint only transfer shear stress and no moment transfer.

This theory supposes that the vertical shear, the normal force, and the bending moment in the board are so small that can be ignored when the deflection is much thinner than the thickness of beam (plate). The hinged joint between the hollow plate only transfers the vertical shear stress (It is also called hinged force).

(2) In order to simplify the calculation, let us suppose that the load on the bridge is distributed according to sinusoidal distribution, so does the vertical shear.

(3) Let us suppose that each plate only produces the vertical displacement and rotation under eccentric load and no lateral bending.

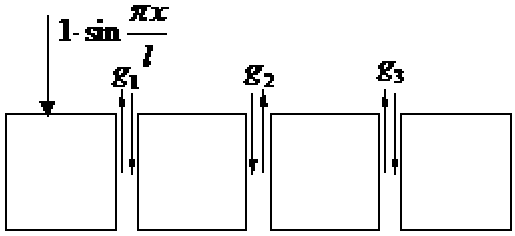

Figure 1. Force of hinge and sinusoidal load

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As shown in figure 1, give a simply supported hollow slab bridge with three hinge joints connected four hollow plates as an example, where relay a sinusoidal unit load $p(x)=1\cdot\sin(\frac{\pi x}{l})$ which produces the joint force $g_1(x)$, $g_2(x)$, $g_3(x)$ in three hinged joints. Simultaneously, every plate gets its sinusoidal load η, and lines them together then got the Lateral Line Distribution. Among them:

$$\begin{aligned}\eta_{11}&=1-g_1\\ \eta_{12}&=g_2-g_1\\ \eta_{13}&=g_3-g_2\\ \eta_{14}&=g_3\end{aligned} \tag{1}$$

The equation for the force of hinge can be obtained in accordance with the statically indeterminate structure mechanics principle. They're shown as follows:

$$\begin{aligned}\delta_{11}g_1+\delta_{12}g_2+\delta_{13}g_3+\delta_{1p}&=0\\ \delta_{21}g_1+\delta_{22}g_2+\delta_{23}g_3+\delta_{2p}&=0\\ \delta_{31}g_1+\delta_{32}g_2+\delta_{33}g_3+\delta_{3p}&=0\end{aligned} \tag{2}$$

δ_{ik} and δ_{ip} are the deformation on the peak of a bridge. Equations can be derived from Figure 1 and Figure 2 as follows:

$$\begin{aligned}&2(1+\gamma+\beta)g_1-(1-\gamma)g_2\\ &=1-(1-\gamma)g_1+2(1+\gamma+\beta)g_2-(1-\gamma)g_3\\ &=0-(1-\gamma)g_2+2(1+\gamma+\beta)g_3=0\end{aligned} \tag{3}$$

$\gamma=5.8\frac{I}{I_1}(\frac{b_1}{l})^2$ is regarded as the ratio of torsion and deflection of main girder; $\beta=390\frac{Id_1^3}{l^4h_1^3}$ is regarded as he ratio of Cantilever deflection and the deflection of main girder. γ and β can be obtained from the section properties of components and brought them into the third equation. g_1, g_2, g_3 can be derived, then the transverse load-distributing influence line can be obtained. However, in practice, the value β is often neglected for it close to zero.

3 FINITE ELEMENT MODELING

This paper selects one assembly type hollow plate girder bridge as the research object. The bridge is 12. 6m span, 0. 6m high, and is made by 9 beams whose width is 0. 99m. Put 1cm horizontal rabbet on reserve for connection with concrete hinge joint. There's a concrete surfacing layer of 8cm(E= 3.0×10^4 MPa). Choose a tri-axial freight car of totally 300KN for static test and take a load efficiency which is 0. 87 and perform it on the most adverse position[ii]. For C40 which is concrete in the bridge deck and hinge joint, the elastic modulus is 3.25×10^4 MPa, and the Poisson ratio is 0. 1667. Set 9 steel bars of $\phi16$ in the top of each plate and 92 steel bars of ϕ_5^s in bottom of each plate.

Homogenize the steel and the concrete elastic modulus to a uniform one, so an Integral model can be built[7]. In this model, the unit SOLID65 is used to simulate the concrete ofassembly type hollow plate Girder Bridge, prestress the reinforcement simulated by link8 element which was prestressed in cooling method. The link between the rod unit and the entity unit was achieved by the degree of freedom coupling using node of same location. On one hand, this simply supported bridge has three displacements to constraint, U_x, U_y, U_z. On the other hand, there is only one displacement to constraint, and it is U_y. In the end, with assist of Mesh200, this bridge has meshed into 50592 elements and 69747 nodes [8].

4 COMPARISON OF THE CALCULATED RESULTS BETWEEN THE FINITE ELEMENT ANALYSIS AND HINGE-JOINTED PLATE METHOD

Compare the calculated value of hinge-jointed plate method to the deflection value of finite element model as shown in Figure 2, the transverse distribution coefficient can be obtained by using the formula $\eta_i=\frac{w_i}{W}$ (deflection of single plate / deflection of all plates)[9]. As shown in Figure 3, line them into one figure with influence line of the transverse load distribution calculated by the hinge-jointed plate method:

As shown in Figure 2, the value of deflection in finite element is slightly smaller than the calculation results of hinge-jointed plate method. And the displacement curve of calculation results is steeper than the finite element results, but their power transmission form is roughly the same. The reason for the differences mentioned earlier is that the hinge-jointed plate method just considers the pavement layer as the even load without considering the synergistic effects of the pavement layer and the hinge joint. However, in the finite element analysis, pavement layer was taken

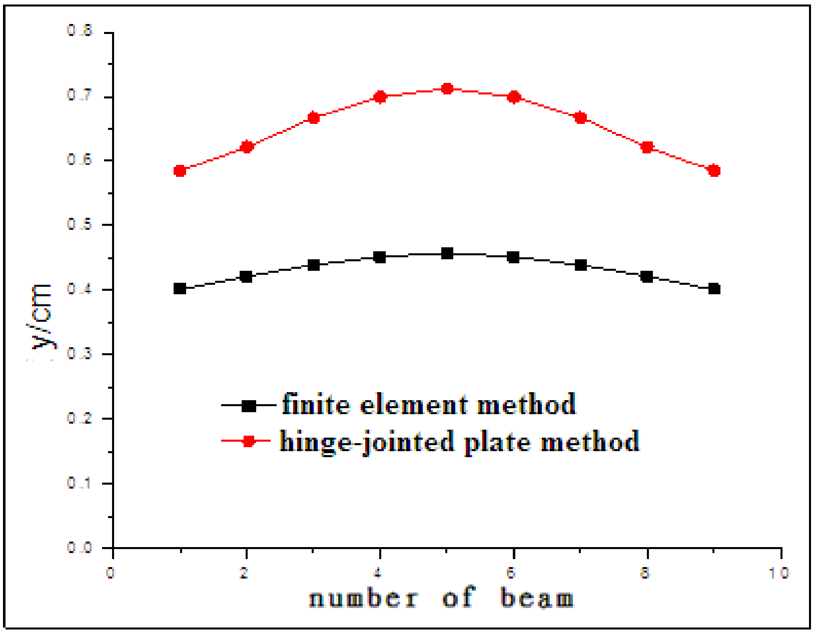

Figure 2. Displacement distribution in the mid-span

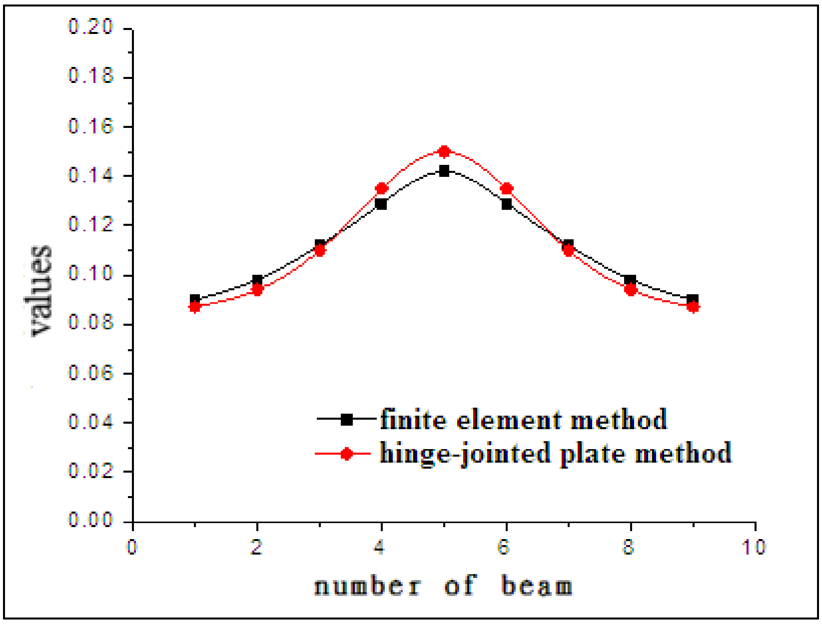

Figure 3. Transverse load-distributing influence lines

into account to work better with the hinge joint, which strengthens its integral rigidity. So it is reasonable for the finite element calculation has a smaller deflection and a more smooth displacement curve. Meanwhile, Figure 3 proves that the transverse distribution coefficient values acquired from the finite element method and hinge joint plate method are fit very well. On the other hand, it also provides that the finite element analysis can react the force transferring form of hinged hollow plate girder bridge well, and it also can be regarded as an effective method for the next step analysis.

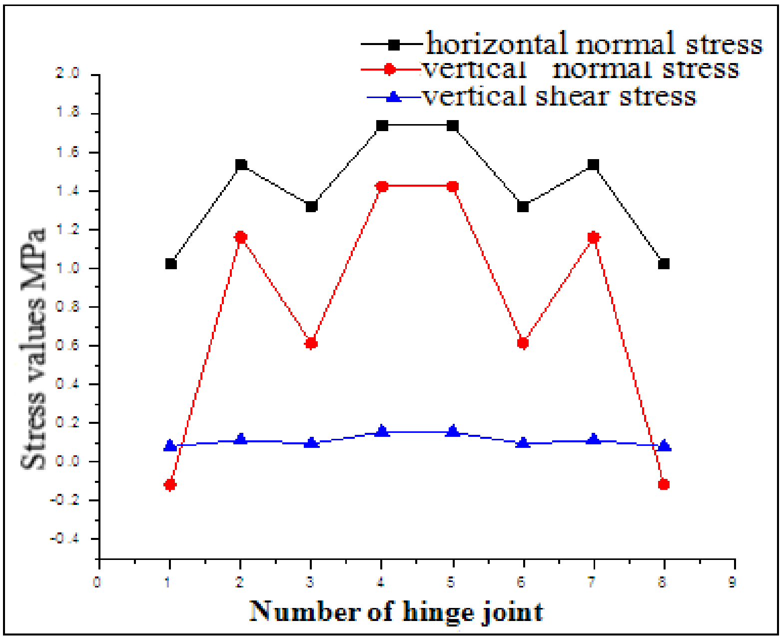

Figure 4. Displacement distribution in the mid-span

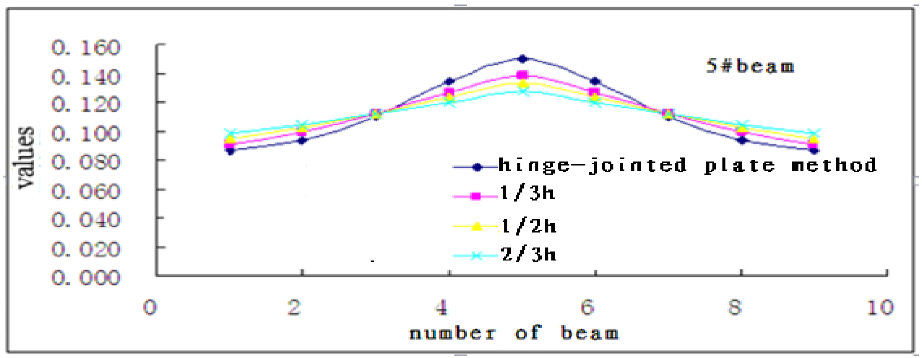

Figure 5. Transverse load-distributing influence lines

5 CONSIDERATION OF CONCRETE INTERFACE CONNECTING HINGE JOINTS TO BEAM SLAB

The hollow slab bridge of assembly type will form a new-old concrete adhesive interface. The construction steps are used to pour the joint after completing the deck lifting. Jian Liu, a Ph. D. of Dalian University of Technology, did a splitting tensile and axial tensile test to compare the test cubes' mechanical behavior. One in which is disposable pouring and another one has a new-old concrete adhesive interface. According to his paper, the splitting tensile strength of the cube has a new-old concrete adhesive interface which is 51.1%~84.2% times greater than the disposable pouring test cube; and the axial tensile strength is 67.4~84.2% times greater than that one. Thus, we can found that the adhesive interface of component having a new-old concrete will reduce the concrete tensile strength [iii]. At the same time, a test to explore the cubes mechanical behavior having new-old concrete adhesive interface is done under tension shear and compression shear state. This experiment proves that the existing of tensile stress can cut down shear strength to some extent[iv]. For the hollow slab bridge of assembly type, the tensile stress in the hinge joint will cut down the shear-bearing capacity and destroy joints. Hence the effect to the shear strength of the new to old concrete interface must be considered when calculating and using the hinge-jointed plate method. And this conclusion is consistent with the formation of cracks in the actual engineering.

6 FINITE ELEMENT ANALYSIS OF THE STRESS OF HINGE JOINTS

Compare the maximum value of the longitudinal stress of the 8 joints, the transverse stress and the shear stress of the concrete interface in the finite element model, we can find that.

According to Figure 4, the vertical and horizontal normal stress values are larger than the vertical shear stress under the middle load. For concrete C40 modeling theory used in this paper, whose axial tensile strength standard value is 2.39N/2 (mm). However, there is still some safety reserve so that there's no need in theory to consider the destructive effect of longitudinal and transverse normal stress to hinge joints. However, as the serious overloading and existence of old to new concrete interface between the joint and the plate, the minimum tensile strength of concrete in hinge joints left is only 1.617MPa after considering the reduction in 67.4%-84.2%. Its safety is greatly reduced or even negative as the longitudinal and transverse normal stress respectively reached the maximum value of 1.735MPa and 1.671MPa. In this case, the longitudinal and transverse normal stress will also damage the hinge joints. The assumption of hinge-jointed plate method theory is said that the hinge joints only withstand the shear stress is unreasonable. The hinge joint is not just a simple shear and the horizontal and vertical normal stress can also have negative effects on it.

7 CONSIDERING HINGE JOINTS DEPTH

At present, according to the general design of hollow plate girder bridge, the hinge joint is divided into three forms as shallow hinge joints (1/3h), middle hinge joints (1/2h) and deep hinge joints (2/3h). The hinge-joined plate method is believed that the tongue and groove joint can be good to transfer the shear forces, even a very shallow hinge joint, could meet the shear strength design requirements. But the reality is that the failure probability of shallow hinge joints is always greater than the other two kinds of forms. For this, the paper built the finite element model about the three forms of hinge joints based on the bridge mentioned earlier to analyze the lateral force transmission of beam slab and the force of hinge joints own as shown in Figure 5.

From the Figure 5, with the hinge joint deepening, the transverse load-distributing influence line of the plate tends to be gentle, and the lateral connection between boards tends to be enhanced. There are two reasons to explain that. One is that with the hinge joint deepening, the resisting shear area which is increased increases the overall stiffness of the bridge; another one is that as the hinge joint deepens, it increase the construction area, so that the vibration of concrete is more uniform, and the concrete placement quality can be guaranteed. In addition, it can be shown from the Table1 that under the action of the middle of the load, with the hinge joint deepening, the vertical stress is gradually decreased. The maximum reduction rate reached 1.7%; the maximum horizontal stress and the vertical shear stress are gradually increased; the maximum growth rate respectively reached 44.3% and 42.3%. The growth of the vertical shear stress makes the influence line of transverse distribution more uniform, the horizontal stress transmission capability of the plate is reinforced; however, at the same time, with the transverse tensile stress increasing, the hollow slab and hinge joints concrete adhesive interface is in tension and becomes weaker and weaker. This is why in the actual engineering, the horizontal hinge joints damage is always started with the lower edge of the adhesive surface of the hinge joints. Obviously, the hinge joints are not just a shear failure; the transverse tensile stress also has a certain destructive effect.

In summary, the deepening of hinge joints can enhance the transverse connection between the plates, however, for the hinge joint itself, the increased transverse tensile stress, simultaneously, will damage the hinge joint concrete adhesive interface. Thus, the hinge-joined plate method that ignores the influence of hinge joint depth is unreasonable, it should be considered to a certain extent.

8 CONSIDERING PAVEMENT EFFECT

As the design of bridges in China, the bridge deck pavement is always applied as a constant load, and it is only considered when it plays the role of distributed load. But in fact, the pavement work can work together with the bridge deck and the hinge joint in increasing the whole stiffness of the bridge to some extent, and have beneficial effects on the transverse distributed load. In this regard, this paper is also based on the finite element model, compared the deformation and the stress values of bridge deck under the two kinds of conditions that give consideration or no consideration to pavement, and had a analysis to the transverse load distribution of the bridge based on the different thickness of pavement as shown in Figure6.

From the displacement image numerical table, we can obtain that the maximum deflection is 4.588mm and the stress values is 3.08MPa of considering the pavement effect, and they are respectively 82.6% and 78.4% with no pavement effect. Therefore, considering the pavement will have a certain impact on the stress and deformation of hollow board, and it can strengthen the transverse connection and reduce the deformation and stress effect of plate at the same time.

As shown in the Figure 7, the transverse load-distributing influence line for the 5# board is under the action of different thickness of pavement. It can be shown that, with the increase of the pavement thickness, the transverse connection between beam and slab was enhanced, and the overall stiffness of the bridge was improved. However, with the increase of the thickness of pavement, the load on bridge beam will be increased to a certain extent. So the overall stiffness of the bridge will not keep increasing but reach a critical value in a thickness range.

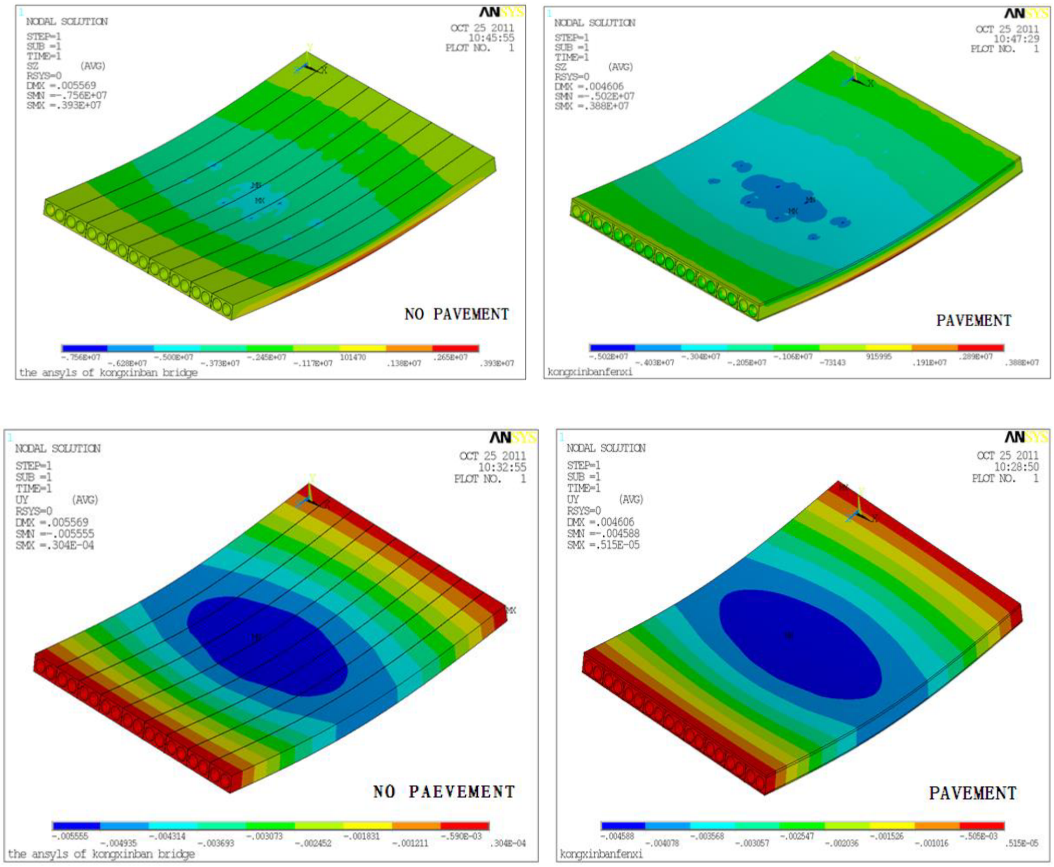

Figure 6. Cloud picture of displacement and stress

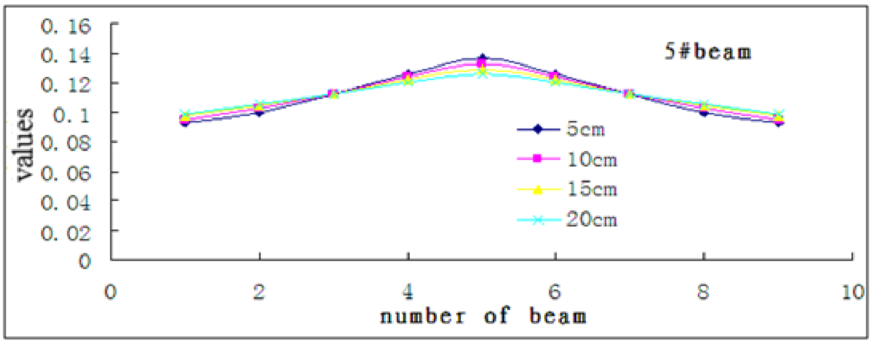

Figure. 7 transverse load-distributing influence lines

In terms of this bridge model, it is better at 5cm-10cm.

In summary, the pavement will also have an impact on the transverse-connection between beam and board. In the design of the hinge-joined plate method, the pavement and its thickness should be also taken into account.

9 CONCLUSION

By comparing the finite element analysis to the connected slab method, and exploring the force performance of hinge joint, we can find that:

The assumption of hinge-jointed plate method is reasonable to calculate the transverse distribution

Table 1. Stress of hinge joint

Hinge joints form	stress(MPa)	Hinge joint 1	Hinge joint 2	Hinge joint 3	Hinge joint4	Hinge joint5	Hinge joint6	Hinge joint7	Hinge joint8
Shallow	Horizontal normal stress	1. 019	1. 531	1. 321	1. 735	1. 735	1. 321	1. 531	1. 019
	Transverse normal stress	-0. 118	1. 161	0. 612	1. 422	1. 422	0. 612	1. 161	-0. 118
	Vertical shear stress	0. 081	0. 114	0. 096	0. 154	0. 154	0. 096	0. 114	0. 081
Middle	Horizontal normal stress	1. 026	1. 487	1. 394	1. 705	1. 705	1. 394	1. 487	1. 026
	Transverse normal stress	0. 024	1. 712	1. 48	2. 552	2. 552	1. 48	1. 712	0. 024
	Vertical shear stress	0. 028	0. 122	0. 026	0. 267	0. 267	0. 026	0. 122	0. 028
Deep	Horizontal normal stress	1. 057	1. 421	1. 465	1. 685	1. 685	1. 465	1. 421	1. 057
	Transverse normal stress	0. 298	2. 793	2. 278	4. 083	4. 083	2. 278	2. 793	0. 298
	Vertical shear stress	0. 17	0. 277	0. 094	0. 440	0. 440	0. 094	0. 311	0. 17

coefficient which is based on the finite element analysis results. And the results are basically the same with the calculation result of traditional hinge-jointed plate method in the power transmission form. However, it is not reasonable for the assumption that the hinge joint are only under the shearing force without tension. Actually, except the condition which is under the vertical shearing force, the joint is also affected by the transverse and longitudinal stress.

The study is also used to find that the new-old concrete adhesive interface between the hollow beam plate and the hinge joints will greatly reduce v the tensile strength of the hinge-jointed concrete. Hence more attention should be paid to the new-old concrete adhesive interface in the calculation of the transverse distribution coefficient, and the hinge-jointed plate method is necessary.

The depth of hinge joint and the thickness of pavement also have impacts on the transverse connection. Although we don’t know the relationship between them now, we should consider the pavement effect in the design of the hinge-joined plate method.

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