Study on the Mechanical Behavior of the Deckpavement by the Whole Bridge – Local Box Girder - Orthotropic Plate Threestage Method

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Abstract: The mechanical analysis of the traditional orthotropic plate local model can not simulate the real deformation state of the bridge deck pavement. Therefore, this paper adopts "the whole bridge - local girder - orthotropic plate" three stage mechanics analysis method. The simulation analysis model of whole multi-tower and multi-span bridge was established to obtain the dynamic response characteristics of whole bridge and the boundary conditions of local box girder model. According to the calculation results of the local box girder model, the most adverse area of dynamic response for deck pavement was found. The local orthotropic plate composite model was established to calculate the most adverse stress, strain and interlaminar shear stress of the deck pavement. The calculated results can be used as the main technical indexes of bridge pavement materials and structural design.

1 INTRODUCTION

The large span steel bridge has developed rapidly in recent decades. Due to the advantages of self-weight and span., most of the steel bridge deck is adopted orthotropic structure. The thin layer asphalt concrete was generally used as paving layer on the large span steel bridge. The pavement layer and the orthotropic plate bear the external load together. Therefore, the pavement layer and the orthotropic plate need to be analyzed as a whole when analyzing the mechanical deformation of the pavement layer(Qian, 2001and 2005). Due to the effect of steel plate stiffening rib, there is obvious stress concentration in the contact position between the paving layer and the stiffening rib. The maximum stress and mechanical properties of the pavement layer can not be calculated accurately by using beam board theory. The most effective analytical tool for solving this problem is the finite element analysis method(Ai, 2017; Chen, 2016; Zhou, 2007).

But in past research, the boundary condition of the model was often simplified, and the influence of whole bridge characteristics was not considered(Zhang, 2017; Yang, 2018). This paper innovatively developed the three-stage analytical method. The displacement value obtained by the whole model in the previous stage is used as the boundary condition of the local model in the latter stage. This method can simulate the mechanical response more accurately of the bridge deck pavement, and the calculated results can be used as the main technical indexes of bridge pavement materials and structural design.

2 THE MECHANICAL RESPONSE OF WHOLE BRIDGE MODEL

2.1 Finite Model of Whole Bridge

The whole bridge model is set up based on finite displacement theory. The main tower and pier are all simulated by the space beam element. stiffening girder was simulated by shell element. The bridge deck pavement and railings are simulated by mass unit which is only considered its mass and not considered its rigidity.

2.1.1Simplifythe Components of Main Bridge

When establishing the suspension bridge model, the key is to simplify the bridge tower, main cable, sling and bridge deck.

1) Main cable and derrick

In order to make the analysis method more universal, space beam element was selected to simulate the main cable.The derrick is the link between the stiffening girder and the main cable which is mainly pulled. The bar element was used to simulate the derrick in this study. The connection diagram of main cable and derrick is shown in Figure 1.

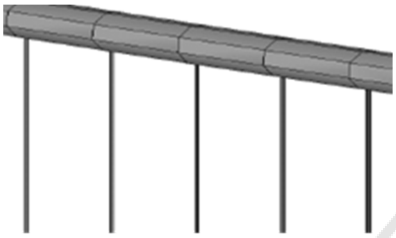

Figure 1: The connection diagram of main cable and derrick.

2) Stiffening girder

In addition to the bridge panel and floor, the steel box girder of the bridge has a large number of diaphragm plate and stiffening rib. The structure is very complicated.If the finite element model is generated directly by the actual structure, the number of units is inestimable and the computation workload is huge.

In the premise of ensuring the consistency of dynamic and static parameters, the equivalent model of composite box girder with different materials is used to equivalent the original stiffening beam.The vertical bending stiffness, transverse bending stiffness, torsional stiffness, mass distribution and mass inertialdistribution of the model are equivalent to the entity.In this study, the orthogonal anisotropic shell element is adopted to carry out the dispersion of the suspension bridge stiffening beam.

3)Main tower

The finite element model of the main tower can be directly generated on the main tower. However, this model has too many grid， and it will cost too much time in computation. In this study, the column and horizontal beams are treated as beams, the cross-section beam element has same cross section characteristic, material and quality with the object.

2.1.2 Section Properties and Material Parameters of Each Component

The section properties and material parameters of each component for the whole bridge are shown as Table 1.

Table 1: Section properties and material parameters of each component.

Component	A/m^2	J_d/m^4	I_y/m^4	I_z/m^4	E/Pa	$\rho/(kg/m^3)$
Main girder	1.56	8.21	192	3.02	2.1×10^{11}	7850
Main cable	0.327	0	0	0	2.0×10^{11}	7850
Derrick	0.005	0	0	0	2.0×10^{11}	7850
Main tower	1.556	7.26	7.2	5.59	2.1×10^{11}	7850
Edge tower	29.6	365	293	180	3.4×10^{10}	2600

In Table 1, A is sectional area; J_d is torsional moment of inertia; I_y is transverse bending moment of inertia; I_z is vertical bending moment of inertia; E is elastic modulus; ρ is density.

2.1.3 The Loading of Main Bridge

In this paper, the deck pavement deformation of the orthotropic steel bridge under constant load and automobile load is analyzed, and the related load is as follows.

1)The constant load of stiffening girder

The first period of constant load: q_1= 178.1kN/m (standard section), q_1 = 213kN/m (special section, 36m on both sides of the main tower);

The second period of constant load: q_2= 53.1kN/m.

2) Cable system

Main cable wire: 50.3kN/m; Wire: 0.96kN/m; Main cable inspection walkway: 0.316kN/m; Cable clamp and sling: 6.382kN/m (middle span), clamps 1.079kN/m (side span); Main cable surface coating: 0.012kN/m.

3) Vehicle load

According to the highway bridge general specification, vehicle load is chosen as highway -I level which is applied by influence line method.

2.1.4 Finite Element Model

The appropriate beam element and shell element were selected to establish the whole bridge model. The concrete model is shown in the Figure 2 and Figure 3.

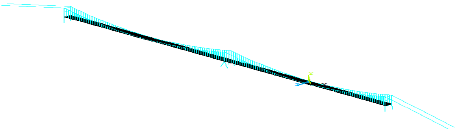

Figure 2:Simulation model of whole bridge.

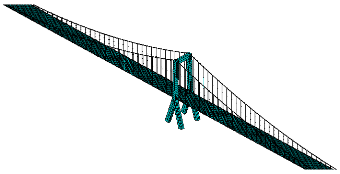

Figure 3: Local model of the structure near the main tower.

2.2 The Mechanical Response Analysis of the Whole Bridge

2.2.1Basic Dynamic Response Characteristics

The modal analysis of the bridge is carried out to study the difference between the three tower and two span suspension bridge and the other two tower suspension bridges. According to the results of the whole bridge, the technical requirements of the deck pavement system can be studied. The calculation results of Taizhou bridge are compared with the two tower suspension Bridges, such as Jiangyin Yangtze river bridge, Runyang Yangtze bridge and other bridges as shown in Table 2.

Table 2 The comparison of self-vibration characteristics between different suspension bridge.

Vibration mode	Taizhou bridge (2*1080m)	Runyang bridge (1450m)	Jiangyin bridge (1385m)	Single span bridge (1080m)
First order positive symmetrical vertical bending	0.1171	0.1241	0.1344	0.1496
First order negetive symmetrical side bending	0.0712	0.0884	0.0920	0.0852
First order positive symmetrical side bending	0.1016	0.0489	0.0509	0.0704
First order negetive symmetrical side bending	0.0765	0.1229	0.1169	0.1153
First order negetive symmetrical torsion	0.2454	0.2698	0.2747	0.3203

Due to the bridge tower was effectively anchored by the main cable of side span and greatly enhance the structure stiffness, the frequency of each order for the two tower bridges was significantly improved in addition to first order positive symmetrical side bending compared with three tower suspension bridge. The anchorage effect for the main cable of side span is very important to improve the structure stiffness of the suspension bridge. The anchorage effect of the middle tower for the three tower suspension bridge is relatively weak. The vertical deflection of the main girder under vehicle load increase significantly relative to the two tower suspension bridge, the torsion ability of main girder decreases, the biggest torsion angle increases, and it also produces new requirements for bridge deck pavement system.

2.2.2 The Most Adverse Position of Deck Pavement in the Whole Bridge

The stress of the main beam is mainly bending moment. The force analysis can be equivalent to the bending bar. The greater the bending moment of the main beam is, the greater the relative deformation of the adjacent units in the main beam and the deck pavement under the active load is. The longitudinal tensile stress of deck pavement will be more evidently influenced by the mechanical characteristics of the whole bridge. Therefore, the vertical bending moment is used as the control index to select the most adverse section of main beam.

Figure 4: Vertical bending moment envelope of the whole bridge.

Table 3:The bending moment range of each control section for the whole bridge.

Control section	Middle tower	1\2 main span	1\4 main span	1\8 main span	1\16 main span	Side tower
Bending moment 10^4 (kN · m)	-14.75~15.54	-4.07~7.78	-3.73~7.47	-3.84~7.52	-4.01~7.82	-2.31~7.32

As shown in Figure 4 and Table 3, the maximum vertical bending moment is $1.55*10^5$kN·m under constant load and the most adverse vehicle load located at the position which is 20m from the middle tower. The minimum vertical bending moment is -1.47*10^{5}kN·m located at the location of the middle tower. Therefore, the 64m box girder near middle tower of the suspension bridge is selected as the most adverse box girder with the maximum stress as shown in Figure 5.

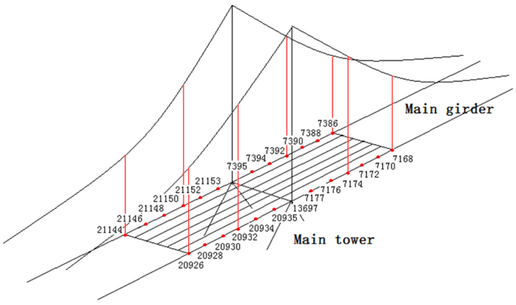

Figure 5: Diagram of the most adverse girder section.

3 THE MECHANICAL RESPONSE OF LOCAL BOX GIRDER

In order to reflect the local beam section of the model under the mechanical characteristics of the whole bridge environment, when establish the model of local beam section, not only the boundary condition should be extracted from the whole bridge, but also the force condition must be consistent with the corresponding beam segments in the whole bridge model. The node displacement on both ends of the beam section of box girder was extracted, after linear interpolation the node displacement was added as boundary conditions of local box girder model.

Take the section of node 20926 and 7168 in Fig.5 as an example, the external forces and the displacement obtained by the whole bridge simulation are loaded to the most adverse local box girder section. The bending moment loading diagram is shown in Figure 6.

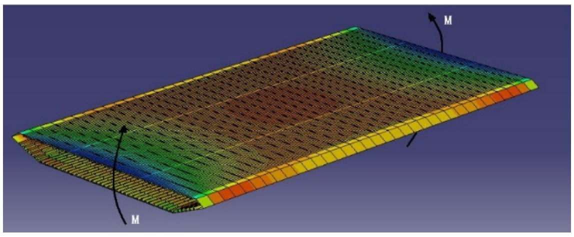

Figure 6:The bending moment loading at the beam-end of local box girder.

The purpose for the 3-d finite element calculation of local box girder model is to determine the stress concentration area of the bridge deck slab under the action of vehicle load as shown in Figure 7. The boundary condition at the most adverse area of the deck pavement was obtained which will be used at the next stage calculation.

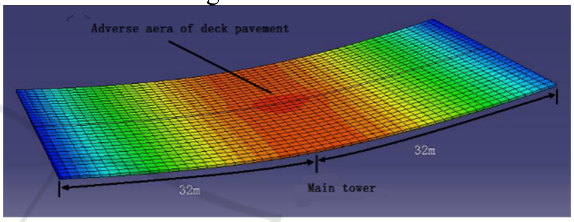

Figure 7: The force adverse area of the deck pavement.

4 THE MECHANICAL RESPONSE OF LOCAL ORTHOTROPIC PLATE COMPOSITE MODEL

In order to obtain the mechanical response of the most adverse deck pavement, local orthotropic plate composite modelwas established by using the boundary condition of the local box girder model calculated in previous section. The load was applied with the highway I-level, and the impact coefficient was 1.3. The axial load in calculation was 140kN and the tire pressure is 1.00MPa as the pavement load standard.

Steel bridge deck is a kind of structural orthotropic structure. During the calculation, the steel bridge deck is assumed as uniform, continuous and isotropic elastic material. The geometric dimensions and material parameters of each component in steel bridge deck are shown in Table 4.

Table4:The geometric dimensions and material parameters of steel bridge deck.

Thickness of steel deck pavement （mm）	Size of U rib （mm）	Spacing of U rib （mm）	Diaphragm thickness （mm）	Diaphragm spacing （m）	Poisson ratio of steel plate	Elastic modulus of steel plate （MPa）
14	300×280×6	600	12	3.2	0.3	210000

The deck pavement is completely attached to the steel bridge deck. In order to improve the calculation accuracy, the unit near the loading area is divided more subtly in the process of discretization as is shown in Figure 8.

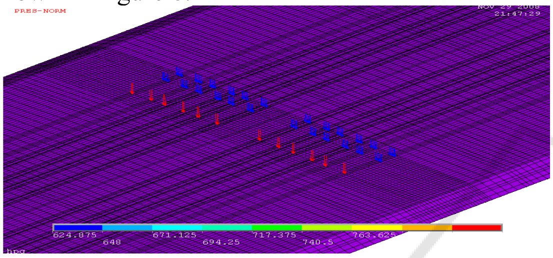

Figure 8: The composite model of bridge paving system.

The calculation and analysis of bridge paving system considers the effect of mechanical response of the whole three tower two span bridge. In the past calculation, the influence of bridge characteristics was not considered, and the boundary condition of the model was often simplified. This paper innovatively developed the three-stage analytical method. The displacement value obtained by the whole model in the previous stage is used as the boundary condition of the local model in the latter stage. This method can simulate the mechanical response more accurately of the bridge deck pavement. Figure 9 is the displacement calculation diagram of the composite model.

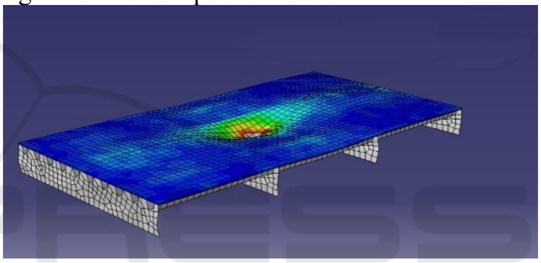

Figure 9: The displacement diagram of the composite model.

Table 5:The mechanical control index value of the composite model under the standard axial loading.

Constraint condition	Pavement surface tensile stress (MPa)		Pavement surface tensile strain ($\mu\varepsilon$)		Maximum interlayer shear stress (MPa)	Maximum deflection span ratio between U rib
	Transverse	Longitudinal	Transverse	Longitudinal		
The internal force of whole bridge as constraint	0.919	0.556	835.4	423.1	0.506	1/1063
Simplified constraint	0.787	0.506	721.0	407.8	0.452	1/1169

The calculation of local orthotropic plate composite model considered two kinds of constraint condition as Tab.5. The calculation results show that the whole bridge structure has obvious influence on the stress of pavement layer. The maximum stress and strain of the composite model considered the force situation of whole bridge is about 17% greater than the simplified constraint model. Therefore, it can be considered that the influence coefficient of the bridge structure of Taizhou bridge on the local force of pavement layer is 1.17. The main purpose of the local orthotropic plate model calculation was to obtain the most adverse stress, strain and interlaminar shear stress of the deck pavement. The calculated results can be used as the main technical indexes of bridge pavement materials and structural design.

5 CONCLUSIONS

This paper innovatively developed the "whole bridge - local girder - orthotropic plate" three-stage analytical method. Through this method, the influence of the whole bridge characteristics is considered when analyzing the mechanical properties of the orthotropic deck pavement. Therefore, the mechanical analysis of pavement structure will be closer to the actual situation.

By the calculation of the local orthotropic plate model, the most adverse stress, strain and interlaminar shear stress of the deck pavement were obtained. The maximum stress and strain of the composite model considered the force situation of whole bridge is about 17% greater than the simplified constraint model. Therefore, it is necessary to consider the whole bridge characteristic when calculating the pavement layer. Meanwhile, the calculated results can be used as the main technical indexes of bridge pavement materials and structural design.

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REFERENCES

1. Ai C, Zhang Y, Al-Kahtani M S M, 2017. Mechanical Characteristics of Asphalt Pavement on Bridge Deck under the Braking Force of BRT Buses. Journal of Southwest Jiaotong University, 52(4):685-693.
2. Chen, L., Qian, Z., Wang, J, 2016. Multiscale numerical modeling of steel bridge deck pavements considering vehicle–pavement interaction. International Journal of Geomechanics, 16(1).
3. Qian Z D, Jian L, Jing M M, 2005. Mechanical analysis of asphalt concrete paving projects on steel bridge deck. China Journal of Highway & Transport, 18(2):61-64.
4. Qian Z D, Huang W, Mao Q, 2001. Mechanical analysis of Nanjing Second Yangtze River bridge deck pavement. Journal of highway and transportation research and development.,18(6):43-46.
5. Yang M, Kainuma S, Jeong Y S, 2018. Structural behavior of orthotropic steel decks with artificial cracks in longitudinal ribs. Journal of Constructional Steel Research, 141:132-144.
6. Zhou Z G, Yang J J, Liu X Y, 2007. Mechanical response of pavement layers on the steel-box-girder-bridge deck. Journal of Changsha University of Science & Technology.
7. Zhang M, Qian Z D, Xue Y C, 2017. Research on steel bridge deck pavement mechanical response of Urumqi express way. Materials Science and Engineering Conference Series.