Shear strength analysis of the stud in steel-UHPC composite bridge deck

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Abstract: In the steel-UHPC lightweight composite bridge deck, the UHPC layer is connected to the steel plate of the orthogonal steel bridge deck through headed steel stud connectors. In order to form a strong combination, it is necessary to ensure that the studs have sufficient shear strength. By establishing the local finite element model, the interlaminar shear stress between the UHPC pavement and the steel deck in the new steel-UHPC composite bridge deck is computed, and the influence of loading factors such as various wheel loading conditions is considered. The results show that the maximum transverse interlaminar shear stress is about twice of the maximum longitudinal interlaminar shear stress. The maximum transverse shear stress under action of bi-axle loading is about 1.33 times of that of the single axle loading. The shear strength of the headed stud meets the requirements of the Chinese standard, USA standard and the European standard.

1. Introduction

Attributed to its light weight, high bearing capacity, rapid construction speed, easy to maintain, orthotropic steel bridge decks have been widely applied to long-span bridges all over the world. However, a lot of engineering experiences indicate that there are two major technical challenges existing in orthotropic steel bridge deck: fatigue cracking and conventional asphalt pavement failure [1].The traditional solution is to improve the weld details or increase the thickness of the steel plate of the orthotropic steel bridge deck, but the problems mentioned above still remain unsolvable fundamentally. The application of ultra-high performance concrete (UHPC) with high elastic modulus and high tensile strength to the orthotropic steel bridge deck provides a new direction for solving the above problems. Shao et al. [2] proposed a new steel-UHPC composite deck structure which connecting the UHPC layer to the steel deck by stud connectors. The results show that the UHPC pavement can significantly enhance the integral rigidity of the composite structure, which can effectively eliminate the risks of steel plate fatigue cracking and pavement damage.

The UHPC layer is connected to the orthogonal steel bridge deck through headed steel stud connectors. Therefore it is important to calculate the shear strength of the stud. With the application of UHPC in bridge engineer, the research on interlaminar shear stress of the steel-UHPC composite structure received extensive attention. Zhang et al. [3] took Dongting Lake Bridge with open-rib steel-UHPC composite deck as engineering background and analyzed the effect of the wheel loads on the interlaminar shear stresses.

The distribution of the interlaminar shear stresses in the steel-UHPC composite bridge deck with closed-ribs is more complex than that of the orthotropic steel decks with open-ribs. Taking a steel-UHPC composite bridge deck consisting of closed U-ribs in North China as engineering background, this paper firstly computes the distributions of the interlaminar shear stresses between the UHPC layer and the steel plate of the bridge, and then evaluates the shear strength of the steel stud connectors based on the design code of, respectively, China, USA and Europe. It is demonstrated that the steel studs in the steel-UHPC composite bridge deck under consideration meet the requirement of all the aforementioned design codes.

2. Finite element analysis model of interlaminar shear stress of steel-UHPC composite bridge

2.1 Establishment of local finite element model

This study is based on a bridge in North China. The thickness of the deck plate is 14 mm, the span between the two neighboring diaphragm beams is 3.2 m, the height and thickness of the diaphragm beam are 700 mm and 10 mm respectively. The thickness of U-rib is 6 mm, the span between the two neighboring U-rib is 300 mm, the bottom length of the rib is 184 mm and the height is 260 mm. The material used in the orthotropic steel decks is Q345q steel. The elastic modulus of the material is 206 GPa and the Poisson's ratio is 0.3. The bridge originally was paved by double layers of modified asphalt SMA pavement, which had to be repaired due to severe damage. In order to improve the resistance of the pavement and fatigue life of the steel box girder, the steel-UHPC composite bridge deck was used, as shown in Figure 1.

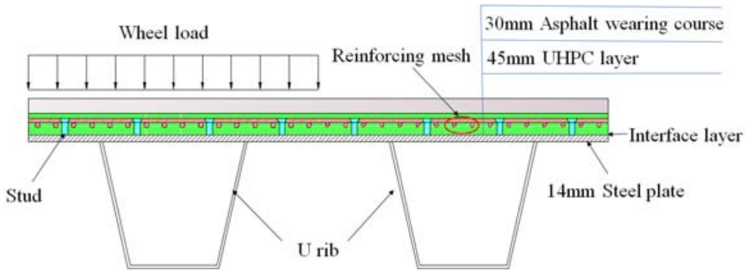

Figure 1 The structure of new steel-UHPC composite bridge deck

In the new pavement system, the studs with the height of 40 mm and the diameter of 13 mm were welded on the top plate of the steel box girder, and the distance between the two studs both in transverse and longitudinal direction are 150 mm. Then the HRB400 reinforcement fabric of 10 was reattached, and the spacing of the reinforcement was about 37.5 mm by 37.5 mm. At last, the 45 mm thick UHPC layer was pouring to form a composite deck structure. The material parameters of the steel-UHPC composite deck system are shown in Table 1.

Table 1 Material parameters

Material	Elastic modulus/GPa	Poisson's ratio	Density/(kg•m-3)
steel	206	0.3	7850
UHPC	42	0.2	2800
asphalt	1	0.2	2400

A local finite element model of a composite bridge deck with four floor beam and five U-ribs is established using ANSYS as shown in Figure 2. The pavement layer is modeled by SOLID45 in ANSYS, the thickness direction of the UHPC layer is divided into four layers. The asphalt layer is divided to two layers. The deck plate is modeled by SOLSH190, the floor beams and the longitudinal ribs are all modeled by SHELL181. The maximum size of the elements is 10 mm to ensure the accuracy of the calculation results. The total number of elements in the finite element model is 518,920. In the calculation, it is assumed that the pavement is an isotropic elastomer, and the connection between the deck plate and the UHPC is perfectly bonded. The displacement boundary conditions of the model is to constraint the displacements in the x-direction at one cross-section of the bridge deck, the displacements in the y-direction at one side of the floor beams and the displacements at the z-direction at the bottoms of the two outer floor beams.

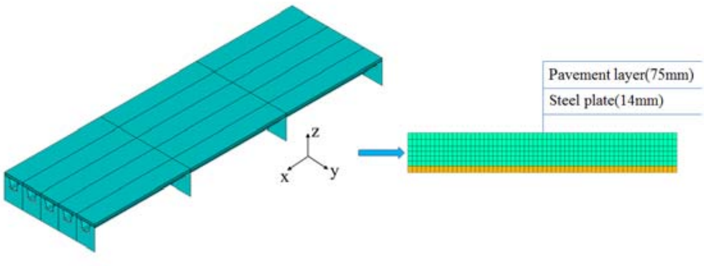

Figure 2 Local finite element model of composite bridge deck

2.2 Selection of vehicle load

The standard five-axle truck [4] shown in Figure 3 is taken as the design load. The load of the dual wheels of the last two axles is 70 kN. The vehicle load is applied to the middle span as shown in Fig 2, and the loading area of dual wheels is 0.2 m×0.6 m. Generally, the calculation of the interlaminar shear stress of the orthotropic steel bridge deck considers only the load of vehicle's single axle [3]. However, the results of Shi et al. [5] showed that it is necessary to consider the effect of the loads of the bi-axles on the stress evaluation of the bridge deck structure when the two adjacent axles are acting on the same span. Therefore, this paper will consider the effect of the double-axle load on the interlaminar shear stress of the composite pavement. Three commonly used methods of wheel loading are adopted, namely In-between-rib loading, Riding-rib wall loading and Over-rib loading as shown in Figure 4. In each loading condition, the wheel loading is moved 100 mm measured from a reference floor beam.

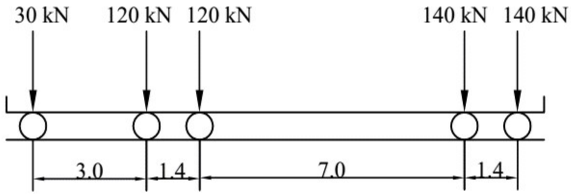

Figure 3 The axle loads of standard five-axle truck (the length unit is in meter)

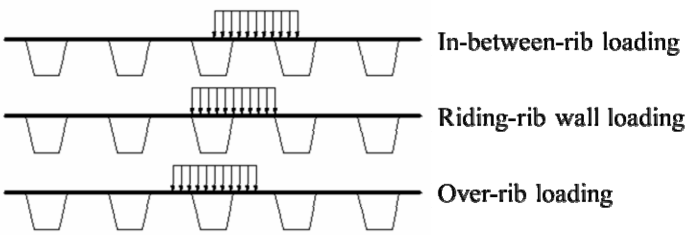

Figure 4 Three transverse positions of wheel loading

3. Interlaminar shear stress of steel-UHPC composite bridge deck

Due to the large difference of the elastic modulus between the UHPC and the steel, there is a large shear stress between the UHPC and the deck plate under vehicle load. In order to ensure the effective connection of steel-UHPC composite bridge deck, the stud connector is used to realize the co-action of the UHPC and the deck plate. So it is very important to ensure the carrying capacity of the stud. In this section, the maximum interlaminar shear stress between the UHPC layer and the deck plate in the new steel-UHPC bridge deck structure under various wheel loading conditions is calculated.

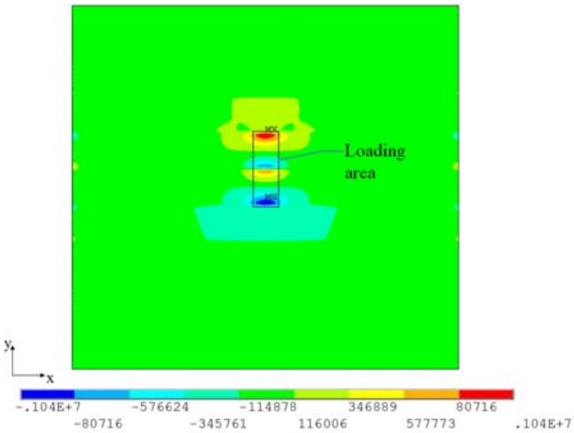

Figure 5 The distribution of maximum interlaminar transverse shear stress under the single axle load of standard truck

Three transverse positions of wheel loading shown in Figure 4 are selected, and the interlaminar shear stress of the new steel-UHPC composite bridge deck is calculated by using the single axle wheel load of the rear axle of the standard five-axle truck. Taking Riding-rib wall loading for example, the maximum transverse shear stress distribution under the single axle loading of the standard vehicle is shown in Figure 5, and the calculation results of the maximum interlaminar shear stress under the single axle loading of the standard vehicle in different loading position is shown in Figure 6.

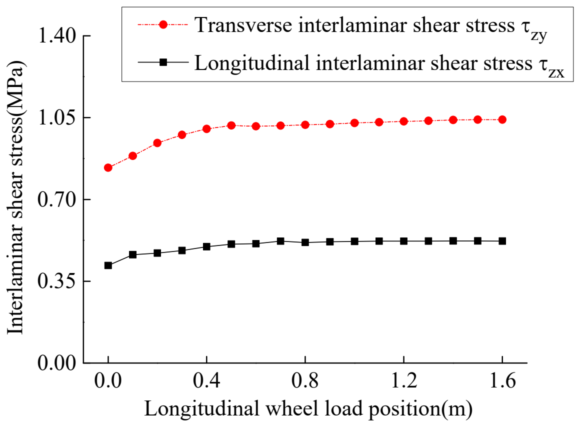

Figure 6 The maximum interlaminar shear stresses under different positions of the single axle load of standard truck

Figure 5 shows that the position of the maximum transverse shear stress under the single axle loading of the standard vehicle is located at the edge of the vehicle loading range. Figure 6 shows that under the single axle loading, with the increase of the distance between the wheel load and the floor beam, the interlaminar shear stress increases slowly, then becomes stable at a distance of 0.4 m from the floor beam, and reaches its maximum at the midspan of two floor beams.

The maximum interlaminar shear stress is used as the criterion to determine the most dangerous position of the shear force. The maximum interlaminar shear stress under different positions of the single axle load of standard truck in three transverse positions is demonstrated in Figure 7. It can be seen from Figure 7 that the maximum transverse interlaminar shear stress of the steel-UHPC composite bridge deck is about twice the maximum longitudinal interlaminar shear stress, so it plays a decisive role in the safety analysis of the studs. In the three common transverse positions of wheel loading, there is little difference of the interlaminar shear stress between In-between-rib loading and Over-rib loading. The maximum interlaminar shear stress generated under Riding-rib wall loading, which is the most disadvantageous transverse load position of wheels.

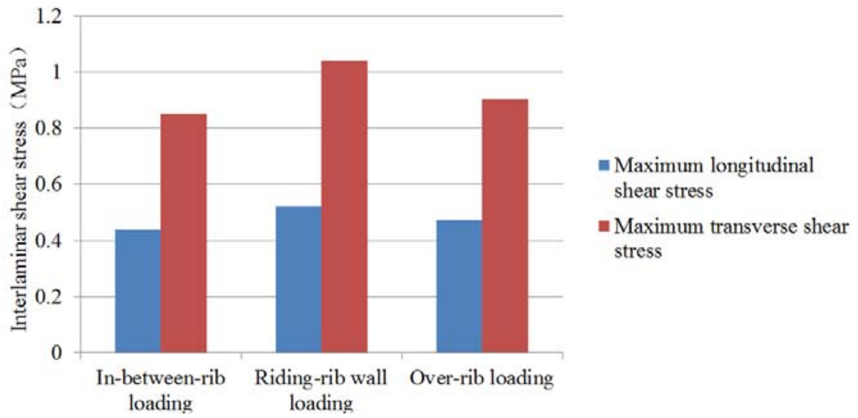

Figure 7 The maximum interlaminar shear stresses under single axle load of standard truck

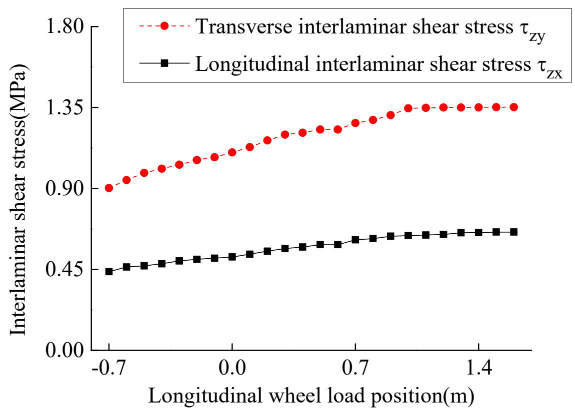

Figure 8 The distributions of maximum interlaminar shear stresses under bi-axle load of standard truck

After analyzing the most disadvantageous loading position, a further study on the influence of the bi-axel loading on the interlaminar shear stress of the new steel-UHPC composite deck structure is carried out. The maximum interlaminar shear stresses as a function of the different loading positions under bi-axle loads of standard truck are plotted in Figure 8. It can be seen from Figure 8 that the interlaminar shear stress of the steel-UHPC varies greatly along the longitudinal direction under the bi-axle loads. In the condition of bi-axls loading, due to the wheel load increased to bi-axls loading at a distance of 0.4 m from the floor beam, the interlaminar shear stress continue to increase and reaches its maximum at the midspan of two floor beams.

Table 2 shows the peak values of interlaminar shear stresses of the steel-UHPC lightweight composite bridge deck structure under different wheel loading conditions. One can see from Table 2 that the manner to apply the wheel loading has a great influence on the evaluation of the maximum interlaminar shear stress. The maximum transverse shear stress of the bi-axle load is about 1.33 times of that of the single axle load, which illustrates the necessity of considering the bi-axle load in the stress evaluation.

Table 2 Peak values of interlaminar shear stress of steel-UHPC composite bridge deck structure under different wheel loading conditions

	single axle loading	bi-axle loading
maximum transverse interlaminar shear stress	1.040 MPa	1.352 MPa
maximum longitudinal interlaminar shear stress	0.522 MPa	0.658 MPa

4. Shear strength checking of the stud connectors based on different design codes

In order to form a strong interface bonding, it is necessary to check the shear strength of the studs in the steel-UHPC pavement. From the safety perspective, it can be assumed that the shear stress between the UHPC layer and the steel plate is carried totally by the studs [3]. The diameter of the stud under consideration is 13 mm, its height is 40 mm, and the material is ML15A. The shear strength of the stud will be checked by Chinese standard [4], USA standard [6] and European standard [7] respectively.

The formula for the shear strength of the steel stud defined by Chinese standard is:

$$Q_U = 1.19 A_{stud} f_{stud} \left(\frac{E_c}{E_s}\right)^{0.2} \left(\frac{f_{cu}}{f_{stud}}\right)^{0.1} \quad (1)$$

The formula of USA standard is:

$$Q_U = \phi A_{stud} f_{stud} \quad (2)$$

The formula of European standard is:

$$Q_U = 0.8 A_{stud} f_{stud} / \gamma_v \quad (3)$$

In the above expressions, Q_U is the shear strength of the headed stud, A_{stud} is the cross-sectional area of the headed stud, E_c and E_s are the elastic modulus of the concrete and the headed stud respectively, f_{cu} is the compressive strength of the concrete cubes, f_{stud} is the tensile strength of the headed stud, ϕ is load resistance ratio (0.85 is used here); γ_v is resistance partial factor (1.25 is used here). The material and geometric parameters of the headed stud are: E_s = 206 MPa, f_{stud} = 400 MPa and $A_{stud} = \pi d^2 / 4$ = 132.67 mm^2. The material parameters of UHPC are: E_c = 42 MPa and f_{cu} = 140.3 MPa. Substituting these parameters into Equations (1)~(3), the shear bearing capacity of an individual steel stud is, respectively, 41.4 kN given by China standard, 45.1 kN by USA standard and 34.0 kN by European standard.

The distance between the two studs both in transverse and longitudinal directions in the steel-UHPC composite structure of the bridge is 150 mm. Accordingly, the shear strength of the studs corresponding to its shear force capacity is 1.84 MPa resulting from China standard, 2.00 MPa from USA standard and 1.51 MPa from European standard.

It can be seen from Table 2 that the shear strength of the steel studs meets the requirements specified by all the three standards considered here, but the safety factor is not big enough. Especially, the studs have a risk of being cut off under the action of heavily overloaded trucks. Therefore, it is necessary to prohibit the overloaded vehicle running on the bridge in order to meet the strength conditions of the steel stud connector and to ensure that the steel-UHPC composite bridge deck structure can effectively play the role of collaborative work.

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5. Conclusion

In this paper, the interlaminar shear stress between the UHPC pavement and the steel deck in the new steel-UHPC composite bridge deck is computed, in which the influence of various wheel loading conditions, such as the single axle loading and the bi-axle loading, are considered. The following conclusions can be drawn from the calculation results.

(1) The Riding-rib wall loading of wheel transverse position produces the largest interlaminar transverse shear stress between UHPC pavement and the steel deck. The maximum transverse shear stress is about twice of the maximum longitudinal shear stress. Thus the largest interlaminar transverse shear stress plays a decisive role in the safety analysis of the steel stud connectors in the steel-UHPC combined bridge deck.

(2) The choice for the wheel loading of the vehicles has a great influence on the evaluation of the interlaminar shear stress in the steel-UHPC composite bridge deck structure. The maximum interlaminar transverse shear stress induced by the action of the bi-axle loading is about 1.33 times as much as that induced by single axle loading.

(3) The shear capacity of the headed steel studs meets the requirements of the Chinese standard, the USA standard and the European standard. However, its factor of safety is rather small. Therefore, the traffic of overloaded vehicles must be strictly restricted.

(4) In this study, the bonding strength between the UHPC layer and the steel plate is ignored. Actually there has interface bonding strength. How to reasonably consider the interface shear strength between UHPC layer and the steel plate should be further studied.

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