

Interfacial behaviors of epoxy asphalt surfacing on steel decks

Chen Xianhua Huang Wei Qian Zhendong

(School of Transportation, Southeast University, Nanjing 210096, China)

Abstract: A model for predicting the interface behavior of epoxy asphalt and steel composite beam under negative bending is developed incorporating partial interaction theory. Interfacial slips between the steel deck and the epoxy asphalt surfacing are included in the model with a new parameter of membrane stiffness. A series of analytical equations based on this model are derived to calculate slip and strain at the interface. Also, a numerical procedure for calculating the load responses of simply supported composite beams with concentrated force at the mid-span is established and verified with two samples. Characters of slip and strain at the interface, sensitivities of tensile stress and interface shear stress with material parameters are studied. It can be concluded that interfacial effects decrease the bending stiffness of the composite; hard and stiff bonding material is better for asphalt surfacing layer working at normal to low temperatures, and the damage of the asphalt surfacing layer will be accelerated with the damage accumulation of the bonding coat.

Key words: epoxy asphalt surfacing; steel bridge deck; interfacial behavior; composite beam

An orthotropic steel plate deck must be paved with a wearing surface to provide a durable and skid resistant surface for vehicles. The wearing surface should be well bonded to the top of the deck plate and be regarded as an integral part of the total orthotropic deck system. For the purpose of designing the wearing surface itself, and its adhesion to the deck plate, the wearing surface is assumed to be composite with the deck plate, regardless of whether or not the deck plate is designed on that basis^[1].

For a long time, asphalt surfacing has been thought to fully interact with steel deck plate and develop no slippage across the interface^[2-3]. Cullimore et al.^[4] developed a theoretical analysis for the composite action between steel deck and asphalt surfacing by stress functions. Kolstein et al.^[5] proposed a theoretical analysis for the asphalt-steel composite section considering two extreme cases: full adhesion and complete separation between the two layers. Nakanishi and Okochi^[6] proposed a two span continuous beam model using three layers. A parameter named coefficient of bondage, t , is defined to describe the state of bonding between the steel plate and the base course. Based on the results of Hameau et al., Medani^[7] pointed out that nonlinearity should be considered so as to explore the

interaction between mastic asphalt and steel decks.

Several asphalt surfacing systems, including guss-asphalt, SMA with polymer modified asphalt and epoxy asphalt, have been used as wearing surfacing for orthotropic steel deck plate bridges around the world. Their performances vary from excellent to poor depending largely on local climate, deck plate flexibility, volume of heavy truck traffic using the bridge, and, in particular, the type and thickness of the surfacing^[8-9]. Epoxy asphalt has been widely used in China because of its high performance and perfect achievement in the Second Nanjing Yangtze River Bridge. Other than those thermal-plastic surfacing systems such as mastic asphalt and SMA, epoxy asphalt is a kind of thermal-set material, which is more stable and stiffer than thermal-plastic surfacing materials. The epoxy asphalt mixture is, to some extent, similar to Portland cement concrete due to its irreversible curing process. How epoxy asphalt surfacing interacts with steel deck is so far still unknown to engineers. Huang and Yang^[8] have reported the linear character of epoxy asphalt in composite beams. Interface differential strains were observed by Chen et al.^[9-10], and partial interaction theory (PIT) was suggested to characterize the interfacial behaviors.

1 Theoretical Analysis

Slip at interface is inevitable in steel-concrete and FRP-concrete composite structures, and it can significantly influence the deflection of composite structures. Great efforts^[11-14] have been made to analyze the effects of interfacial slip. The most extensively used

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Biographies: Chen Xianhua (1976—), male, doctor, lecturer, chenxh@seu.edu.cn; Qian Zhendong (1968—), female, doctor, professor, qianzd@seu.edu.cn.

theory is partial interaction theory^[15], developed by Newmark in the 1960s. Three key assumptions are adopted: ① Shear connectors act as a continuous elastic shearing medium along the length of the beam between the concrete and the steel interface; ② Shear at the interface of different components of beams is proportional to slips; ③ The vertical displacement, rotation and curvature of steel and concrete are identical at the same end of an element.

In practice, 50 to 60 mm of epoxy asphalt mixture layers is consistently bonded with steel deck with 0.68 L/m² of epoxy asphalt bonding coat^[8,16]. The interaction between the epoxy asphalt and the steel is similar to that of the composite actions in steel-concrete and FRP-concrete composite structures. The difference is that the bonding coat of epoxy asphalt is more flexible, and the modulus ratio of steel to epoxy asphalt is generally much greater than that of steel to concrete. Both the bond membrane and the epoxy asphalt layers are temperature-dependent materials.

1.1 Basic assumptions

According to the test results of Huang et al.^[8-10], the following assumptions are made based on PIT:

① Material behavior of steel and epoxy asphalt can be considered as linear elastic.

② Thickness of bond membrane can be neglected with regards to steel and epoxy asphalt layers.

③ Shear at the interface of different components of beams is proportional to slips.

④ The vertical displacement, rotation and curvature of steel and epoxy asphalt layers are identical at the same end of an element, which means ignoring up-lift and shear lag of epoxy asphalt layers.

A segment model under negative bending is shown in Fig. 1 based on those assumptions. In Fig. 1, u is the longitudinal displacement at the geometric center of the section; s is the interfacial slip between epoxy asphalt surfacing and steel plate; ϕ is the rotation of epoxy asphalt and steel at the cross section; F is the axis force; Q is the shear force; and M is the bending moment. The subscripts 1 and 2 refer to steel and epoxy asphalt, respectively. The superscript refers to the condition after loading. For example, $F^+ = F + dF$.

Assumption ③ gives

$$\tau = \kappa_i s \quad (1)$$

where τ is the shear stress at interface; κ_i is the membrane stiffness of bond coat; s is the slip at interface.

The relationship between slip and displacement can be derived according to assumption ③ and Fig. 1. It is shown as follows:

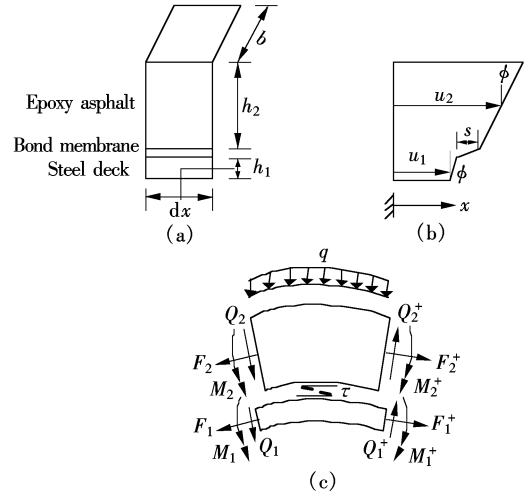


Fig. 1 Segment element model of composite beams. (a) Element of composite beam; (b) Displacement; (c) Internal force

$$u_2 - u_1 = s + \frac{H}{2} \phi \quad (2)$$

where $H = h_1 + h_2$.

Assumption ④ leads to

$$\chi = \frac{d\phi}{dx} = \frac{M_1}{E_1 I_1} = \frac{M_2}{E_2 I_2} = \frac{M_1 + M_2}{E_1 I_1 + E_2 I_2} \quad (3)$$

where χ is the curvature of the cross-section.

1.2 Governing differential equations

The force equilibrium in the vertical and horizontal directions gives

$$\left. \begin{aligned} dF_2 - \tau b dx &= 0 \\ F_1 + F_2 &= 0 \\ dQ_1 + dQ_2 &= q dx \end{aligned} \right\} \quad (4)$$

The moment equilibrium of the epoxy asphalt and steel segments gives

$$\left. \begin{aligned} dM_2 + \frac{h_2}{2} dF_2 &= Q_2 dx \\ dM_1 - \frac{h_1}{2} dF_1 &= Q_1 dx \end{aligned} \right\} \quad (5)$$

According to Eqs. (1) to (5), eliminating u_2 and ϕ , we obtain the governing equation of slip,

$$\frac{d^2 s}{dx^2} = \alpha^2 s - \beta \quad (6)$$

where $\alpha^2 = \kappa_i b \left(\frac{1}{A_0} + \frac{H^2}{4EI} \right)$, $\beta = \frac{HQ}{2EI}$, $\frac{1}{A_0} = \frac{1}{b}$, $\left(\frac{1}{E_1 h_1} + \frac{1}{E_2 h_2} \right)$, $EI = E_1 I_1 + E_2 I_2$.

1.3 Slip and strain at the interlayer

According to Ref. [9], the deflection of surfaced orthotropic deck plate under a double-wheel load at the critical position is characterized with local contra-flexure, which is equivalent to a simply supported beam loaded at mid-span, as shown in Fig. 2.

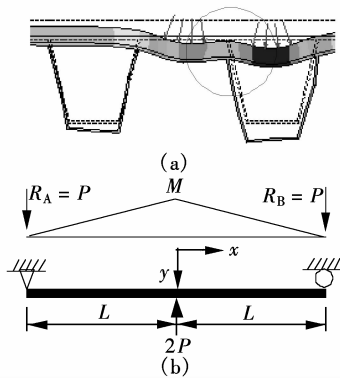


Fig. 2 Equivalent beam of orthotropic deck pavement^[19].
(a) Local deflection; (b) Equivalent beam

The boundary conditions in such a composite beam can be derived according to the structural symmetry^[17] as listed below:

- 1) Zero slip at the mid span of the beam, that is $s(x=0) = 0$.
- 2) There is no difference with interface strain at the tip of the beam, $s'(x=L) = 0$.

Solving Eq. (6) with the boundary conditions we have

$$s = \frac{\beta}{\alpha^2} \frac{e^{-\alpha x}(e^{\alpha x} - 1)(e^{2\alpha L} - e^{\alpha x})}{e^{2\alpha L} + 1} \tag{7}$$

The expression of slip strain at the interface can be obtained by differentiating Eq. (7),

$$\frac{ds}{dx} = \frac{\beta}{\alpha} \frac{e^{-\alpha x}(e^{2\alpha L} - e^{2\alpha x})}{e^{2\alpha L} + 1} \tag{8}$$

Theoretical expressions of strains and deflections can also be deduced from Eqs. (1) to (8).

2 Experimental Verification

In order to further explore the interfacial behaviors of composite beams, a numerical procedure is programmed and verified with experimental results. Two composite beams numbered S-1 and S-2 are sampled and tested with the same procedure as in Ref. [9]. Both beams are 380 mm long and 100 mm wide, with a section of 50 to 55 mm epoxy asphalt layer bonding to 14 mm steel plate^[16]. Nine strain gauges, two for the steel and the other seven for epoxy asphalt, were used to measure the section strain distribution of a composite beam as shown in Fig. 3. An extra strain gauge is used for temperature compensation. A maximum load of 5 kN is applied with an increment of 1 kN at room temperature. Deflection and strains are measured for each load increment.

The measured strains of those two samples are shown in Fig. 4. Obviously strains distribute linearly in each layer, and there exists differential strain at the in-

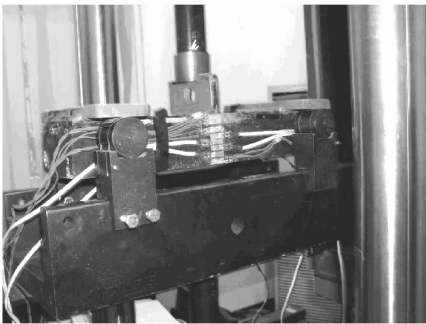


Fig. 3 Photo of composite beam and the test set-up

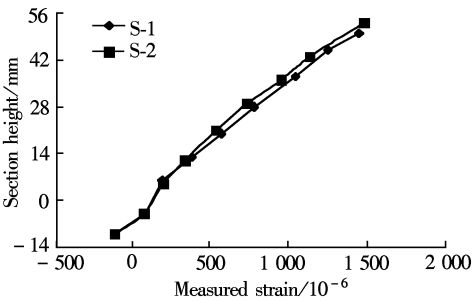


Fig. 4 Test results of strain at mid-span section of composite beam

terface. In order to verify this and calculate interfacial differential strain, the strain of the epoxy asphalt and the steel were regressed respectively with linearity, as listed in Tab. 1. The measured strain marked with crosses and its theoretical distribution are shown in Fig. 5.

Tab. 1 Regression of measured strain

Beam number	Layer	Regression parameters		
		Slope	Intercept	R ²
S-1	Steel	0.031 6	-6.905 3	1
	Asphalt	0.035 8	-0.754 4	0.99
S-2	Steel	0.032 4	-6.756 8	1
	Asphalt	0.037 6	-0.664 9	0.99

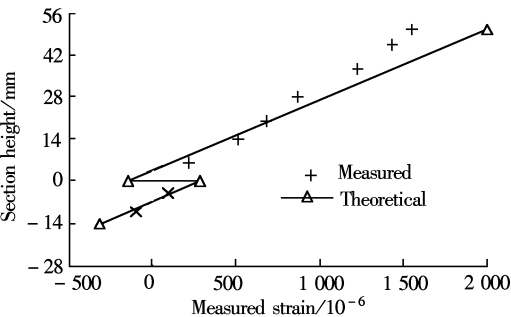


Fig. 5 Comparison of theoretical and measured strain

According to Tab. 1 and Fig. 5, the test results confirm the basic assumptions of the new model. However, it should be noticed that the slope of strain in the epoxy asphalt is about 15% greater than that in the steel deck, and the error between measured strain at the surface of the epoxy asphalt and its theoretical value is about 20%. This error may be caused by two factors:

One is shear lag of epoxy asphalt excluded in the new model, and the other factor is that the measured strain is actually averaged on an area^[18], while the theoretical value is measured on a point.

3 Numerical Analysis

Distributions of interface slip and strain along the beam with a load of 5 kN are shown in Fig. 6. Only half of the beam is included considering the structure symmetry. Both slip and slip strain show steep variations at a range of 30 mm near the mid-span. And both of them decrease as the membrane stiffness of the bonding coat increases.

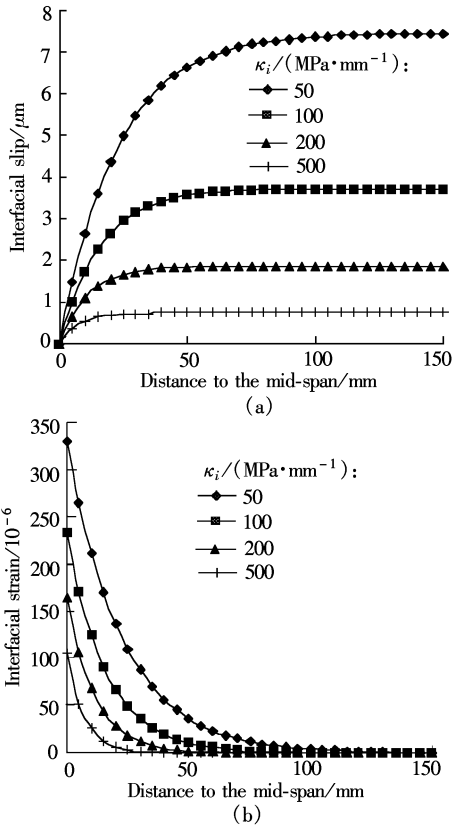


Fig. 6 Interface slip and strain distribution along composite beam

The influences of E_2 and κ_i on the tensile stress of the surfacing layer and interface shear stress are shown in Fig. 7. Significant changes appear when the elastic modulus is larger than 1 500 MPa. Interfacial shear stress increases with stiffer bonding coats, while the tensile stress of the asphalt surfacing decreases. It means that the interaction between the asphalt surfacing and the steel deck at high temperature is mainly influenced by the stiffness of the asphalt surfacing, while at room temperature or even lower, the membrane stiffness of the bonding coat also plays an important role. It can also be concluded that the asphalt surfacing will experience larger tensile stress with the damage pro-

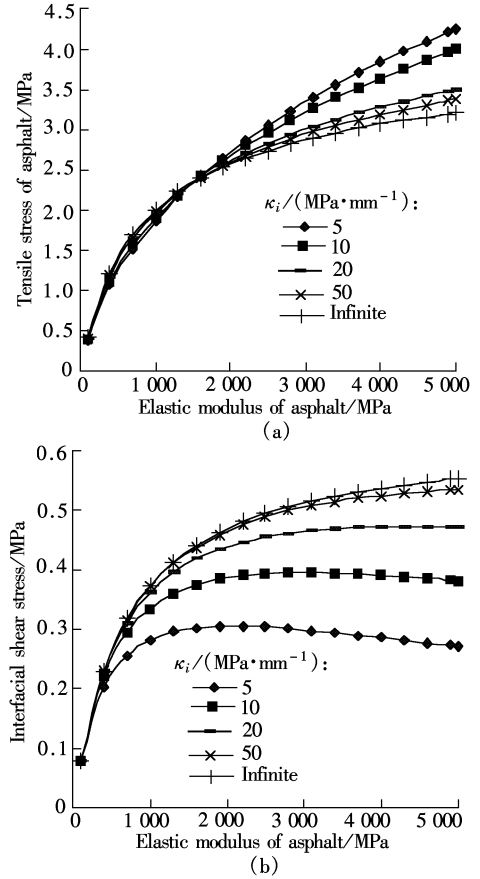


Fig. 7 Influences of E_2 and κ_i on tensile stress and interface shear stress

cessing of the bonding coat, which means that the damage of asphalt surfacing will be speed up with the damage accumulation of bonding coat.

4 Conclusion

The interfacial behaviors of composite beams of epoxy asphalt bonded to steel under negative bending are investigated in this paper. A model for predicting the interface behavior of the composite beam under negative bending at the serviceability limit state is developed. The model considers the slips at the steel-epoxy asphalt interface by a new parameter of membrane stiffness. A series of analytical equations based on this model are derived; a numerical procedure based on the new model is programmed to analyze the flexure responses of simply supported composite beams with concentrated forces at mid-span.

To verify the analytical model and the procedure, two composite beams of epoxy asphalt surfacing and steel are made and tested in the laboratory. The results show that the prediction of the deflection and strain by the proposed analytical method is sufficiently accurate, and the procedure can be used in further study to back-calculate the membrane stiffness of the bonding coat and the elastic modulus of epoxy asphalt. Characteris-

tics of slip and strain at the interface, influences of membrane stiffness and elastic modulus to stress responses are studied. It can be concluded that interfacial effects decrease the bending stiffness of the composite. Hard and stiff bonding materials are preferred for the asphalt surfacing system working at normal to low temperature, and the damage of the bonding coat aggravates the deterioration of asphalt surfacing.

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钢桥面环氧沥青铺装的界面行为

陈先华 黄 卫 钱振东

(东南大学交通学院, 南京 210096)

摘要:通过引入一个新参数膜劲度,在部分共同作用原理的基础上,建立了描述钢桥面环氧沥青混凝土铺装复合梁在负弯矩作用下的界面行为模型,用以分析钢-环氧沥青混凝土之间的界面滑移与应变.推导了弹性工作状态下复合梁的界面滑移与应变的表达式,编制了数值计算程序并用2根复合梁进行了校核.然后采用该程序分析了界面滑移与应变沿复合梁纵向的分布特征,以及铺装层中的最大拉应力、层间剪应力对材料参数的敏感性.结果表明,界面效应削弱了钢桥面铺装复合梁的整体抗弯刚度;中低温条件下,采用劲度更大的粘结层材料有利于改善沥青铺装层的受力;粘结层的损伤累积将加剧沥青铺装层的破坏.

关键词:环氧沥青混凝土铺装;钢桥面板;界面行为;复合梁

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