

Finite element simulation and optimal analysis of surfacing on steel orthotropic bridge deck

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Abstract: To analyze the stress state of steel orthotropic deck pavement and provide reference for the design of the overlay, the inner stress state and strain distribution of surfacing under the load of the deformation of the whole bridge structure and tyre load are analyzed by the finite element method of submodeling. Influence of surfacing modulus on the strain state of the overlay is analyzed for the purpose of the optimal design of the overlay structure. Analysis results show that the deformation of the whole bridge structure has no evident influence on the stress state of the overlay. The key factor of the overlay design is the transverse tensile strain in the overlay above the upper edge of web plate of rib. The stress state of the overlay is influenced evidently by the modulus of rigidity transform overlay. And the stress state of the overlay can be optimized and lowered by increasing the modulus and thickness of rigidity transform overlay. The fatigue test has been done to evaluate the fatigue performance and modulus of different deck pavement materials such as epoxy asphalt, SBS modified asphalt, rospalt asphalt which can provide reference for deck pavement structure design.

Key words: steel orthotropic deck; bridge deck overlay; finite element; submodeling; optimal analysis; fatigue test

The orthotropic deck consists of a deck plate supported in mutually perpendicular directions by a system of transverse crossbeams and longitudinal stiffeners. It may therefore be linked to a plate with dissimilar elastic properties in two directions^[1-2]. While empirical and mechanical design models do exist for the design of ordinary pavements, there is no universally accepted model for the design of surfacing on orthotropic steel bridges. There is a need for a new design procedure for surfacing on orthotropic steel decks. Such a procedure should be based on a proper understanding of the behaviors of the different materials involved, as well as the influence of the geometry of the structure^[3-4]. Some research has been done on the stress state of orthotropic steel bridge surfacing based on independent sections of the whole bridge^[5-6]. Based on the project of Zhanjiang Bay Bridge, the inner stress state under the deformation of the whole bridge and tyre load is analyzed and the optimal design of the surfacing is made by the finite element method of submodeling.

1 Analysis of the Strain State of Surfacing on Orthotropic Steel Deck

The surfacing and orthotropic steel deck constitute a composite structure bearing tyre load. The mechanics analysis has to be made on this composite

structure to understand the performance requirements and design targets for surfacing material. It is hard to study the strain state of the orthotropic steel deck surfacing belonging to the complex structure with transverse crossbeams and longitudinal stiffeners by the traditional beam and plate theory. This problem can be solved by the finite element method. The influence on surfacing from the deformation of the whole bridge and the inner strain distribution rule under tyre load are analyzed separately in the following.

1.1 Influence on surfacing from the deformation of whole bridge

Zhanjiang Bay Bridge is a cable-stayed steel orthotropic bridge with the main span of 480 m, deck thickness of 14 mm, and rib thickness of 6 mm. The computing model is built by shell cell for beam and link cell for cable. Accurate results of the surfacing strain state can be pulled out from analysis using the finite element model. And the view of the model for the whole bridge structure is shown in Fig. 1.

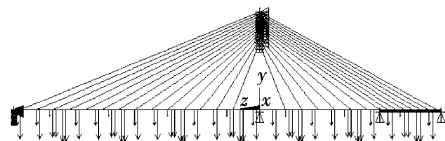


Fig. 1 Computation model for whole bridge structure (half)

The asphalt surfacing as the accessory part of the bridge structure follows deck deformation passively since the rigidity of asphalt surfacing is far less than the rigidity of steel deck structure. The strain state of

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the surfacing is calculated under the whole bridge deformation based on the hypothesis that there are compatibility of deformation and complete continuity between deck and surfacing.

The main beam deflection curves under full load and unbalanced load are shown in Fig. 2. The transverse distribution curves of the longitudinal strain under full load and unbalanced load are shown in Fig. 3. The longitudinal strain curves of deck above the upper edge of web plate is shown in Fig. 4. The curves show that the strain peak value of 185×10^{-6} is at bridge support and intersection of steel and concrete beam. The transverse and vertical strains are smaller than the longitudinal strain. These calculation results show that the deck strain is below 185×10^{-6} and lower than the fatigue limit for common surfacing materials, though the defection is as large as 470 mm. The surfacing material can follow the deformation of the whole bridge. And the full load condition is the event of low frequency and long period, so the de-formation of the whole bridge has little influence on deck surfacing. The deformation of the whole bridge influence on the surfacing can be ignored in the surfacing design for the bridge with a long span.

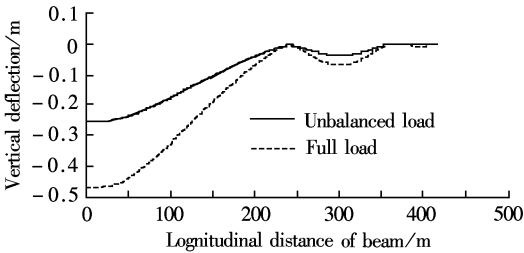


Fig. 2 Deflection curves of the main beam

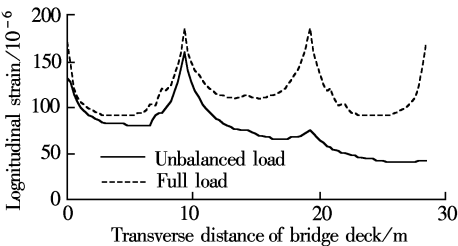


Fig. 3 Transverse distribution curves of the longitudinal strain

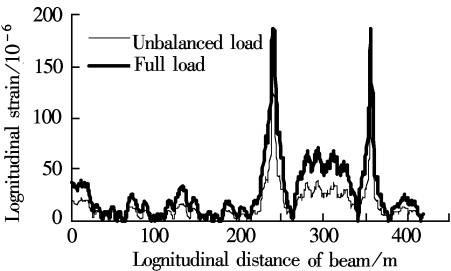


Fig. 4 Strain curves of the deck of the main beam

1.2 Inner strain state analysis of surfacing under tyre load

The finite element model has large numbers of elements if computing the local effect under tyre load in detail by the whole bridge model. And this big finite element model has a very high requirement on the computer and the computing efficiency is low. The independent bridge beam section cannot represent the integrity of the whole bridge structure and boundary condition. The finite element method of submodeling can solve this problem well^[7].

The submodeling method is used two times in one analysis process in this paper. First, the coarse model of the whole bridge with an element dimension of 1 m is created and analyzed. Then the fine model of the beam section with an element dimension of 0.2 m is created and analyzed and the boundary conditions are from the last coarse model. Finally, the finer model of the local deck section with an element dimension of 15 mm is created and analyzed and the boundary conditions are from the last model. The model of the third step is created by the 3-D solid element with eight nodes. The surfacing thickness is 70 mm and the modulus is 2 GPa. The tyre load of 0.70 MPa is applied as two surface loads of 0.2 m \times 0.25 m with 0.1 m space between the load areas. The distribution character of transverse strain(*x* direction) of the surfacing is analyzed, due to the fact that the transverse strain has the dominant effect on the surfacing. The spatial view for distribution of transverse strain (*x* direction) of the surfacing is shown in Fig. 5. The strain distribution shows that tensile strain is located on the upside of the surfacing above the upper edge of web plate of rib, and the peak value of the tensile strain is 240×10^{-6} .

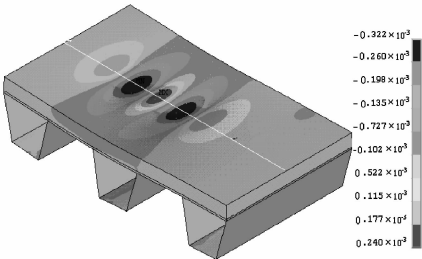


Fig. 5 Spatial view of transversal tensile strain distribution

2 Optimal Analysis and Design of Surfacing Structure

2.1 Principle of optimal design of surfacing structure

There is great rigidity difference and sharp stress change between steel deck and surfacing. A rigidity

transition layer (RTL) with high modulus can be designed between the steel deck and the wearing layer to adjust and optimize the stress state between the deck and surfacing. The material should have excellent anti-fatigue, anti-shearing, and waterproof character at the same time.

2.2 Scheme of computing and analysis

The strain state of the surfacing under local tyre load is analyzed by the submodeling method based on computing of the whole bridge structure and bridge section structure. The thickness of surfacing is 70 mm and the modulus of wearing course is 2 GPa. The finite element model with the rigidity transition layer of different thickness and modulus is computed separately. The modulus of the rigidity transition layer is 15, 10, 7, 5, 3, 2, 1, 0.5 GPa, respectively and the thickness is 0, 5, 10, 20, 30 mm, respectively in the finite element model. The tyre load of 0.70 MPa is applied as two surface loads of $0.2\text{ m} \times 0.25\text{ m}$ with 0.1 m space between the load areas. The model is based on the assumption that complete continuous between deck and surfacing.

2.3 Influence of modulus and thickness of rigidity transition layer on surfacing strain state

The transversal tensile strain of surfacing is studied in detail because the transversal tensile strain has the dominant influence on the surfacing. The distribution of surfacing strain is analyzed on three section planes A, B and C. The distribution of the surfacing transversal tensile strain for the model with a rigidity transition layer of 10 mm thick and 2 GPa is shown in Fig. 6. The underside of section plane A and the upside of section plane B is obviously in tensile state. The distribution curves of the transversal tensile strain of surfacing are analyzed along the paths where section planes A and C, B and C are intersected.

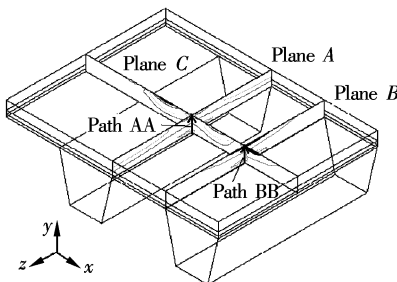


Fig. 6 Section plane of transversal tensile strain of surfacing

First the model with a 30 mm rigidity transition layer is analyzed as an example. The distribution curves of transversal tensile strain of surfacing along

the paths AA and BB are shown in Fig. 7. The curves show that the tensile strain falls down and the curves become more flat along with the increase in rigidity transition layer thickness. The distribution curves of transversal tensile strain of surfacing along the paths AA and BB are shown in Fig. 8. The curves show that the tensile strain decreases obviously along with the increase of the rigidity transition layer modulus.

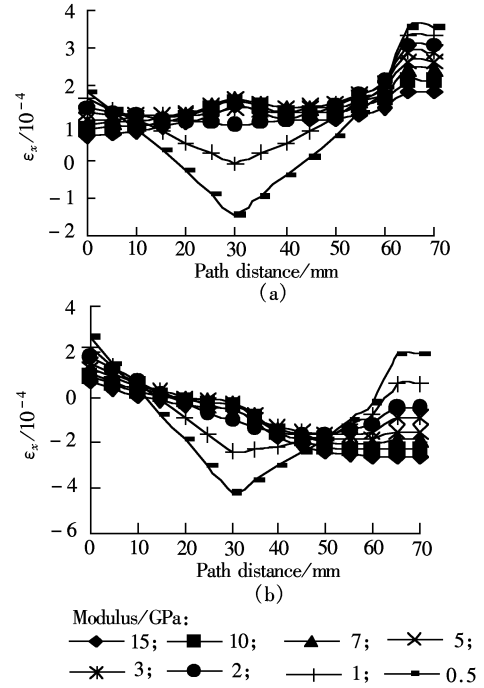


Fig. 7 Curves of RTL modulus influence on ε_x .
(a) Path AA; (b) Path BB

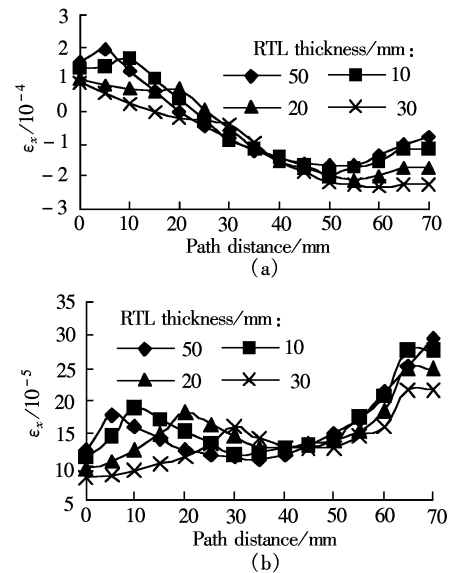


Fig. 8 Curves of RTL thickness influence on ε_x .
(a) Path AA; (b) Path BB

The strain state with a rigidity transition layer of a different modulus is compared to the layer of modulus 2 GPa by

$$P = \frac{x - x_{2\text{GPa}}}{x_{2\text{GPa}}} \times 100\% \tag{1}$$

where P is the percent of strain increase (if positive) or decrease (if negative), x is the strain, and $x_{2\text{GPa}}$ is the strain of the layer of modulus 2 GPa.

The curves of the strain change percent compared to the strain with the rigidity transition layer of modulus 2 GPa (the same as the wearing layer modulus) along with the rigidity transition layer modulus change is shown in Fig. 9(a) for the strain underside and Fig. 9(b) for the strain upside. The curves show that the strain becomes greater when the rigidity transition layer modulus increases and the strain becomes less when the rigidity transition layer modulus decreases.

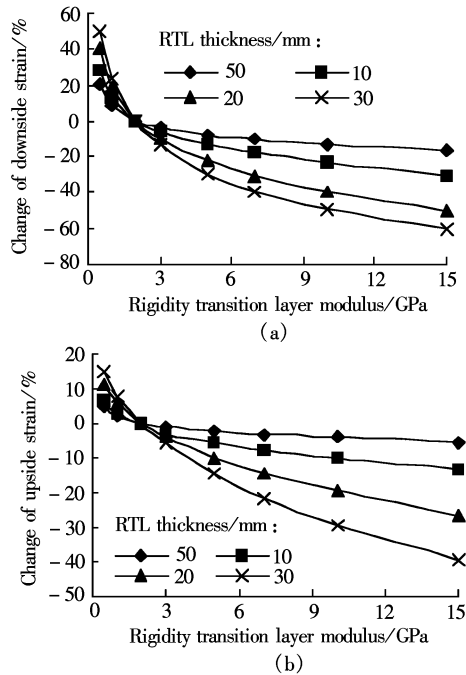


Fig. 9 Curves of RTL modulus influence on stain. (a) Downside; (b) Upside

The curves of the strain change percent compared to the strain with the rigidity transition layer of modulus 2 GPa along with the rigidity transition layer thickness change is shown in Fig. 10(a) for the strain underside and Fig. 10(b) for the strain upside. The curves show that the strain increases as the rigidity transition layer thickness decreases when the rigidity transition layer modulus is bigger than the wearing modulus of 2 GPa and the strain increases as the rigidity transition layer thickness increases when the rigidity transition layer modulus is lower than the wearing modulus of 2 GPa. The strain change percent is basically linear with the thickness change of the rigidity transition layer. The influence of the rigidity transition layer thickness on the strain of surfacing depends on

the relative magnitude of the modulus of the rigidity transition layer and the wearing layer. It is better for the surfacing strain state when the modulus of the rigidity transition layer is higher than that of the wearing layer.

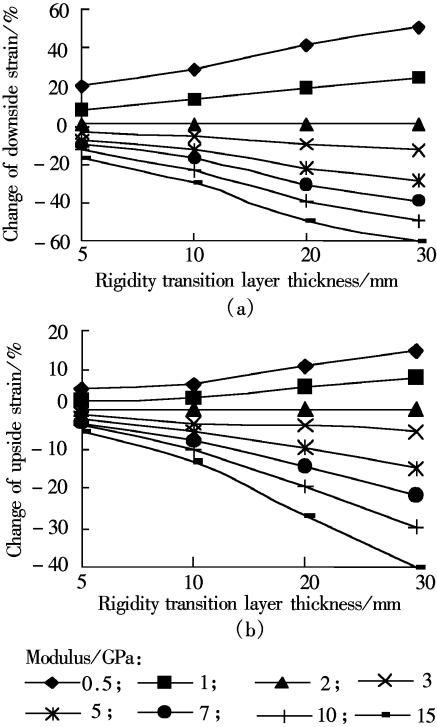


Fig. 10 Curves of RTL thickness influence on stain. (a) Downside; (b) Upside

Optimal analysis above shows that the increase in thickness and the modulus of the rigidity transition layer properly can obviously lower the strain level of surfacing upside and underside.

The fatigue test was done to evaluate the fatigue performance and modulus of different materials such as epoxy asphalt, SBS modified asphalt, Rosphalt asphalt. The fatigue test model is a four-point bending beam. The stress state of the specimen can simulate the stress state of the deck pavement. The model of the fatigue test is strain control and the load frequency is 10 Hz and the temperature is from 15 to 60 °C.

The results of fatigue life at the strain level of 10^{-3} are as follows: epoxy 0.3×10^6 ; Rosphalt 800×10^6 ; SBS SMA 0.12×10^6 . That shows epoxy asphalt has better fatigue performance and Rosphalt has the best fatigue performance. The bending modulus of the specimen at 15 °C shows that epoxy asphalt has the highest modulus over 10 GPa and Rosphalt has the lowest modulus under 1 GPa and SBS SMA 3.28 GPa. The modulus change curves along with temperature are shown in Fig. 11 which shows that the modulus of the specimen is influenced obviously by temper-

ature and the modulus of the specimen decreases when temperature increases.

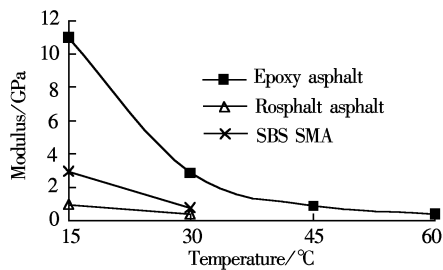


Fig. 11 Modulus change curves along with temperature

3 Conclusions

1) These computing results of the whole bridge structure show that the deck strain is lower than the fatigue limit for common surfacing materials. The surfacing material can follow the deformation of the whole bridge structure. The deformation of whole bridge influence on surfacing can be ignored in the surfacing design for the bridge with a long span.

2) The submodeling method of finite element can analyze the strain state and distribution character of surfacing exactly and in detail. The analysis results show that the tensile strain located at the upside of surfacing above the upper edge of web plate of rib is the dominating factor for surfacing design.

3) The optimal analysis shows that increasing thickness and modulus properly can obviously lower the strain level of surfacing upside and down side.

4) The fatigue test shows that the epoxy asphalt mixture has a high modulus and a long fatigue life and

the Rosphalt mixture has a low modulus and a long fatigue life.

References

- [1] Medani T O. Asphalt surfacing applied to orthotropic steel bridge decks, a literature study (No. 7-01-127-1) [R]. Netherlands: Road and Railroad Research Laboratory of Delft University of Technology, 2001.
- [2] Hulsey J Leroy, Yang Liao, Raad Lutfi. Wearing surfaces for orthotropic steel bridge decks [A]. In: *Transportation Research Record* [C]. Washington, DC: National Academy Press, 1999, **1654**: 141–150.
- [3] Medani T O. Towards a new design philosophy for surfacings on orthotropic steel bridge decks (No. 7-01-127-2) [R]. Netherlands: Road and Railroad Research Laboratory of Delft University of Technology, 2001.
- [4] Medani T O, Scarpas A, Kolstein M H, et al. Design aspects of wearing courses on orthotropic steel bridge decks [A]. In: *Proceedings of the 9th International Conference on Asphalt Pavements (ICAP)* [C]. Copenhagen, Denmark, 2002. 1–5.
- [5] Li Chang, Deng Xuejun, Zhou Shizhong, et al. Analysis of the deck pavement on steel box bridge [J]. *Journal of Southeast University (Natural Science Edition)*, 2001, **31** (6): 14–17. (in Chinese)
- [6] Hu Guangwei, Qian Zhendong, Huang Wei. Structural optimum design of the second system of orthotropic steel bridge [J]. *Journal of Southeast University (Natural Science Edition)*, 2001, **31**(3): 76–78. (in Chinese)
- [7] Xu Wei, Li Zhi, Zhang Xiaoning. Application of submodeling method for analysis for deck structure of diagonal cable-stayed bridge with long span [J]. *China Civil Engineering Journal*, 2004, **37**(6): 30–34. (in Chinese)

正交异性钢桥面铺装有限元模拟和优化分析

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摘要: 为了确定正交异性钢桥面铺装受力状态并为设计提供参考, 运用子模型有限元法分析了桥梁整体变形及局部轮载作用下铺装内部受力状态及应变分布特点. 为优化设计铺装层结构, 分析了铺装层模量对其应变状态影响. 分析结果表明: 大跨径钢桥整桥变形对铺装层受力状态影响很小, 钢桥面铺装设计的控制受力因素是轮载局部作用下铺装层的横向应变, 铺装层模量对铺装层的受力状态有显著影响, 通过提高铺装层刚度过渡层的结构优化设计措施可以显著改善铺装层的受力状态, 降低铺装层的应变水平. 分别对环氧沥青混凝土、SBS 改性沥青 SMA 和 Rosphalt 改性沥青混凝土的模量及疲劳性能进行了试验评价, 可以为桥面铺装结构组合设计提供参考数据.

关键词: 正交异性钢桥面; 桥面铺装; 有限元; 子模型; 优化分析; 疲劳试验

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