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Analysis on cracking of deck pavement on Jiangyin Bridge

Cheng Gang Chen Xianhua Wang Xiao

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

Abstract: Based on four-year field inspection and investigation on deck pavement of mastic asphalt on Jiangyin Bridge, cracking causes of mastic asphalt are studied. Cracks of deck pavement are summarized on crack length and width to get a clear view of their propagations. Traffic surveys including traffic volume, axle load and vehicle speed were also conducted to assess their influences. Samples taken on-site were tested with pulling-out test and fatigue test to benchmark their properties. According to the inspection and tests results, it is concluded that the cracks are induced by rutting and fatigue. Lack of fatigue resistance, not well bonded to the steel deck and insufficient high temperature stability are supposed to be the main reasons as well as high density of low speed, excessively overloaded trucks.

Key words: suspension steel bridge; Jiangyin Bridge; orthotropic deck plate; deck pavement; mastic asphalt; cracking

Jiangyin Bridge is a suspension steel bridge famous not only for its long span but also for its mastic asphalt deck pavement, as shown in Fig. 1. It was the first time[1] that mastic asphalt had been applied on orthotropic deck plate in China. The surfacing system was designed by Scott Wilson Pavement Engineering, installed by Anderson Asphalt Limited in the summer of 1999 and open to traffic in the middle of the autumn of the same year.

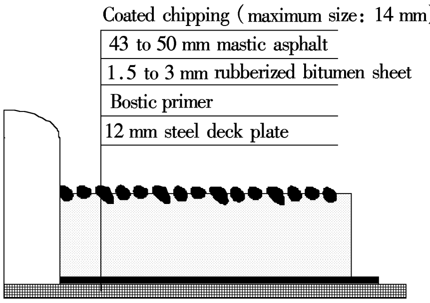
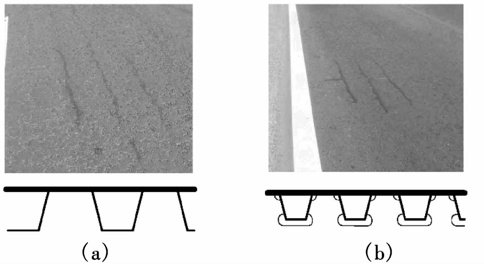


Fig. 1 Deck pavement on Jiangyin Bridge

Transverse cracks were observed several weeks after opening to traffic. Longitudinal cracks were observed that winter. Rutting also occurred in its first summer operation time. Both cracking and rutting propagated rapidly and spread to the whole bridge[2]. This was far beyond expectations. Premature cracking and rutting of the mastic asphalt have endangered traffic safety and increased the probability of corrosion of the steel deck. It is necessary to investigate the damage and its causes not only for rehabilitation, but also for the operation and maintenance of the rehabilitated surfacing system of the bridge and other steel bridges with asphalt surfacing systems. Since surface cracking was observed in the mastic asphalt, inspections and investigations have been regularly carried out at intervals of less than one year by the College of Transportation of Southeast University in order to assess the influence of cracking and to make a proposal for the future renewal of the whole system. This paper sums up the investigation on cracking and its causes of mastic asphalt on Jiangyin Bridge. According to the investigation, this paper concludes that lack of high temperature stability and fatigue resistance, insufficient stiffness and bonding strength, and high density of low speed, excessively overloaded vehicles are the main causes of premature cracking.

1 Cracks and Their Propagations

Longitudinal hair cracks were observed in the surface over the webs of ribs several weeks after its open-day, as shown in Fig. 2(a). In the first winter, transverse surface cracks were also found over the webs of diaphragms and deck, as shown in Fig. 2(b).



(a) (b)

Fig. 2 Surface crack in mastic asphalt found in early operation stage (sealed). (a) Longitudinal crack over the web of U-shape ribs; (b) Cracks over the web of diaphragm

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Biography: Cheng Gang(1951—), male, professor, chengg@ seu. edu. cn.

Longitudinal cracks have a length of 0. 5 to 2 m, a width of 0. 3 to 1 mm. Transverse cracks have a length of 0. 2 to 0. 3 m. A few transverse cracks have also been observed at the pavement beyond diaphragms in the center lane.

Parallel longitudinal cracks over the web of ribs occurred along with short transverse cracks in the winter of 2001, as shown in Fig. 3. The space between two parallel longitudinal cracks was about 5 to 8 cm. The length of longitudinal cracks increased 3 to 5 m, the maximum cracking width was up to 2 mm. Pavements in both nearside and center lanes in two directions were cracking.

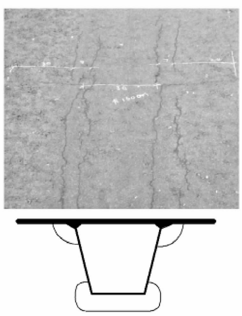

Fig. 3 Cracks found in Nov. 2002

In the winter of 2002, pavements under wheel tracks of nearside lanes were almost cracked transversely at a spacing of 3. 2 m, while in the center lanes, pavements over half diaphragms were found with cross cracks under wheel tracks. Most longitudinal cracks in upper stream direction stretched across at least 6 diaphragms and with lengths close to 20 m on average. The widest crack was 5 to 6 mm, found at the transverse crack close to diaphragms between the 19th and 23rd boom counted from the northern tower. In addition, transverse and longitudinal cracks existed in the repaired part, and the connection of repaired and original pavement parts had cracked as well.

In January, 2003, the transverse cracks extended from 70 to 140 cm, the average width reaching 3 to 4 mm, with the largest close to 1 cm. The longitudinal cracks soon propagated into net cracks. Splitting and sliding occurred with cracking widths of 4 cm at most. Repaving became inevitable two months later along with severe delaminating, slipping and shoving.

2 Investigation Plan and Results

In order to find the exact reasons of premature damage, laboratory test programs and on-site survey including temperature of the asphalt surface and traffic passing through the bridge were launched after cracks occurred. Samples taking on-site and rehabilitation-projects were tested with extraction tests, wheel tests pulling-out tests and fatigue tests to benchmark the properties of its conditions. Pavement temperature was measured by built-in transducers at different layers of the pavements. Traffic surveys were conducted to estimate the equivalent single axle load (ESAL). The survey data was also used in three-dimensional finite element analysis (3-D FEA) to assess the influence of overloading on pavements.

2.1 Laboratory tests

Flexural fatigue tests were conducted to inspect fatigue resistance and dissipated energy of mastic asphalt, as shown in Fig. 4. The composite beam is composed of a 12 mm steel deck and 50 mm mastic asphalt with an interlayer of rubberized asphalt membrane, which is sampled from rehabilitation project. Two samples were tested at room temperature. A 10 Hz sinusoidal load with an amplitude of 6 kN is selected to simulate an axle load of 130 kN passing through the bridge decks. The average fatigue life is 1.5×10^6 with a dynamic deflection of 0. 25 mm before failure.

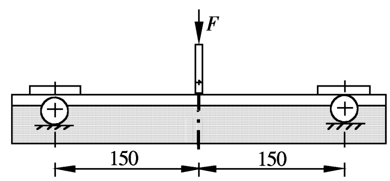

Fig. 4 Fatigue test on composite beam (unit: mm)

A pulling-out test with the composite beams after fatigue was conducted at room temperature, see Fig. 5. Loading rate is about 200 N/s. Eccentricity should be avoided during core drilling and the test. Seven cores were drilled and tested. Bonding strength between mastic asphalt and steel deck plate is 1. 01 MPa, with the highest of 1. 56 MPa and lowest of 0. 71 MPa.

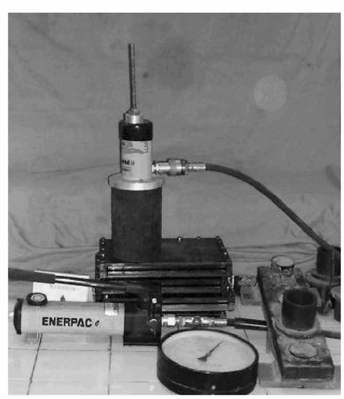

Fig. 5 Pulling-out test machine and samples

2.2 Traffic surveys

Traffic surveys were conducted several times including traffic volume, traffic composition, traffic distribution, axle weight and running speed of trucks. Only trucks were counted. All trucks were classified into four types according to axle number.

The traffic volume was based on statistical results from data provided by Jiangyin Bridge toll stations. Accumulated trucks passing through the Bridge since its opening day was up to 9×10^6, which was nearly half the total traffic volume. The traffic compositions of trucks are percentages of the total trucks calculated by traffic volume data, as shown in Tab. 1.

Tab. 1 Traffic compositions of trucks %

Truck type	Axle number				Total
	Dual	Triple	Four	Five & over	
Composition	64. 23	32. 48	3. 04	0. 25	100

A field traffic survey was conducted to get a clear view of the traffic distribution of nearside lanes. The survey lasted 72 h and in total 1.2×10^4 trucks were recorded passing through the Bridge to Jiangyin. Almost 60% of the trucks were running at the nearside lane. Traffic distributions of nearside lane to Jiangyin are calculated by field survey data, as shown in Tab. 2.

Tab. 2 Compositions and distributions of trucks %

Truck type	Axle number				Total
	Five & over	Dual	Triple	Four	
Composition	52. 06	10. 18	36. 73	1. 04	100
Distribution	46. 87	72. 15	82. 03	91. 67	—

Rear axle weights of heavy trucks were measured by an axle weight detector with random sampling in April, 2001. The survey lasted 48 h and in total 263 trucks were inspected. The results are given in Tab. 3.

Tab. 3 Weights per rear axle of trucks %

Weight per rear axle/kN	Percentage to its own type			
	Dual	Triple	Four	Five & above
50 to 100	48. 46	45. 45	39. 44	66. 67
100 to 130	38. 46	24. 25	22. 22	26. 67
130 to 150	5. 38	12. 12	18. 89	6. 67
over 150	0. 77	3. 03	24. 44	0. 00

Speeds of trucks running at nearside lane to Jiangyin were measured by a radar speed meter on February 20th, 2001, as shown in Fig. 6. Trucks with speed lower than 40 km/h made up approximately 70% of a total of 127 trucks.

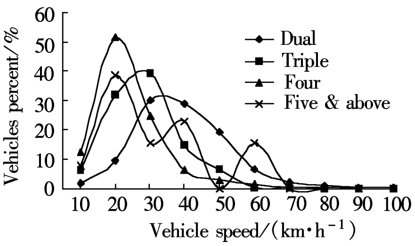

Fig. 6 Speed of trucks running at nearside lane to Jiangyin

3 Analysis and Discussion

3.1 Properties of mastic asphalt surface systems

3.1.1 High temperature properties

Mastic asphalt designed by BS2000 does not meet the high temperature requirements of Chinese criterion[3]. Wheel track tests under different temperatures[4] show that the dynamic stability of the mastic asphalt used at Jiangyin Bridge is highly susceptible to temperature. When temperature rises from 45 to 60 ℃, a sharp decrease in dynamic stability falls from 1 305 to 303 runs/mm. According to on-site temperature observations on deck pavement, days with a temperature of deck pavement over 60 ℃ is almost up to 30% of the whole summer day, which means inevitable ruts and plastic deformation[4] in hot summer.

Severe ruts and plastic deformation weakened flexibility of the mixture and increased the risk of cracking. Pavements under wheel tracks become thinner lowering the stiffness of composite deck pavement system. It means that mechanical conditions of pavements with ruts became worse, considering the reduction of flexibility and stiffness. That is why ruts and cracks occurred at the same zone in succession as observed.

The bonding and waterproofing system of Jiangyin Bridge was composed of solvent bond primer named BOSTIC and a 1. 5 to 3 mm rubberized bitumen blend. The rubberized bitumen blend was combined with 75% Caribit45 supplied by Shell Company and a 25% calcareous mineral filler from England[1]. The existence of the blend raised the asphalt content of the whole asphalt surfacing system, thus to some extent decreasing its high temperature stability.

3.1.2 Fatigue resistance of mastic asphalt

As the high temperature stability of mastic asphalt could not reach the lowest requirement of Chinese Standards, Trinidad Lake Asphalt (TLA) and coarse aggregate content were increased and soluble asphalt content decreased from 8. 25% to 7. 5% to improve its stability[1]. Mastic asphalt's high temperature stability was indeed increased as its dynamic stability increased from 121 to 303 and Marshall stability with a flow value of 5 mm increased from 6. 4 to 7. 8 kN[1]. However, present research[5] has indicated that too much TLA may have bad effects on its low temperature contraction and fatigue resistance althoughit indeed can improve high temperature stability, aging resistance and durability of the mixture. Fatigue tests on samples from rehabilitation projects on Jiangyin

Bridge have also confirmed this. The fatigue life of mastic asphalt under 6 kN is only 1.5×10^6 cycles, which is far lower than 12×10^6 cycles required by the similar suspension bridge of Runyang Bridge[6]. Therefore, poor fatigue properties of mastic asphalt surfacing is a significant cause that leads to its premature cracking.

3.1.3 Efficiency of bonding and waterproofing membrane

Insufficient adhesion or shear strength of bonding coat may lead to slippage and delamination at interlayer of asphalt surfacing and deck plate under wheel load. It could also greatly increase the risk of laceration and squeezing of asphalt surfacing[7], which was corroborated by asphalt surfacing damage at Haicang suspension bridge in Xiamen and Junshan cable-stayed bridge in Wuhan.

According to the pulling-out test, the bonding strength at the interface is about 0.71 to 1.56 MPa, which is only a little greater than the theoretical shear stress under adverse conditions. The value of the bonding strength and shear strength decreased with higher temperature or water permeation. This in turn caused the slippage and delamination of deck pavement.

3.2 Analysis on operation conditions

3.2.1 Mechanic conditions

Firstly, the cracking of asphalt surfacing on the orthotropic steel deck is mainly related to local negative bending[6,8,9]. Transverse tensile stress, which causes longitudinal cracks perpendicular to the stress, occurs at the pavement over webs of U-shape ribs adjacent to wheel load. Longitudinal tensile stress, which induces transverse cracks perpendicular to the stress, occurs at the pavement over webs of diaphragms near to wheel load[6,9].

Secondly, twisting caused by unbalanced traffic load may play some roles in mastic asphalt's damage. The deck plate of Jiangyin Bridge is 32 m wide with 3 lanes in each direction. Heavy trucks going in southbound were much more numerous than those going in the opposite direction. Most heavy trucks going in southbound were running on the outside lane, as traffic survey results shown in Tab. 4. Furthermore, flutter and buffeting under truck and wind are two basic phenomena of long-spanned suspension bridges that may have bad effects on interlayer bonding. Limited to the size of 3-D FEA model[9], influences of twisting and dynamical properties of the suspension bridge on deck pavements are not available yet.

Tab. 4 Influences on the strain of asphalt surfacing with over-loaded truck

Overload ratio/%	Negative/10^{-6} ε_x	Negative/10^{-6} ε_y	Negative/10^{-6} ε_z	Positive/10^{-6} ε_x	Positive/10^{-6} ε_y	Positive/10^{-6} ε_z
0	−817	−728	−292	444	535	80
30	−1070	−793	−315	578	659	109
55	−1281	−875	−387	693	789	131

3.2.2 Traffic conditions

1) Heavy duty and overload traffic

The responses of deck pavement under overloaded trucks are calculated with 3-D FEA, listed in Tab. 4. Equivalent fatigue damage reduction[10] could be used to analyze the effect of overloading with the data in Tab. 4. The fatigue damage caused by an overload of 30% is six times that of standard axle load of BZZ-100, an overload of 50% equals 32 times, an overload of 100% up to 93 times. To draw a conclusion, overloaded trucks tremendously increased bend and shear fatigue damage of asphalt surfacing system. ESAL of BZZ-100 was reckoned based on Ref. [10] and Tabs. 1 to 4. Accumulated ESAL of the outside lane going southbound by the end of 2002 was about 15×10^6, which was far above its fatigue life. Accordingly, heavy traffic and overloaded trucks were the most important causes of the damage.

2) Slow velocity of trucks

Laboratory creep tests and fatigue tests have revealed that mastic asphalt is susceptible to temperature and loading speed. Creep rate increases visibly with temperature[4]. Dissipated energy per cycle decreases as cyclic load frequency goes faster, as shown in Fig. 7. It is obvious that mastic asphalt has its limits in dissipating energy before failure. Thus low frequency which means low speed may shorten the fatigue life of mastic asphalt. Those phenomena mean slowly running vehicles have some adverse effects on mastic asphalt's permanent deformation and fatigue resistance.

3.3 Other causes

The upslope of the southbound approach bridge

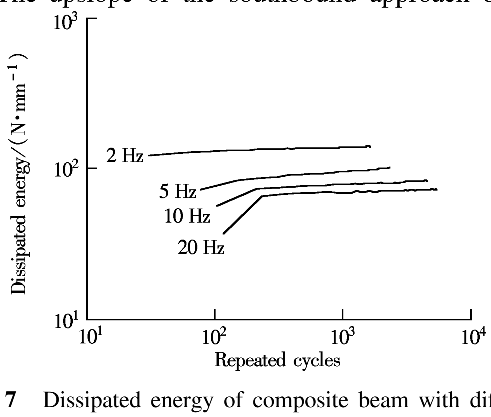

Fig. 7 Dissipated energy of composite beam with different frequencies

to Jiangyin is 2 km longer than in the opposite direction to lower the speed of heavy trucks. This may be an explanation of why the damage of deck plate surfacing in the southbound direction is more severe than that in northbound direction.

During its operation, timely but efficient maintenance can prevent water intrusion and retard the damage. Without reliable maintenance, water or moisture can infiltrate to the bottom of the waterproofing membrane and weaken interlayer adhesion. Cracks develop quickly once pavements lost bonding strength.

4 Conclusion

Rut induced cracks and fatigue cracks were major premature deteriorations of the mastic asphalt surfacing. Lack of high temperature stability and fatigue resistance, inefficient adhesion, overloaded trucks with slow speed, dense and heavy-duty traffic are the key factors leading to the deteriorations.

It is necessary for engineers to accurately appraise local climate and traffic, to choose suitable test methods and technical norms before designing deck pavement. As for Jiangyin Bridge, precautions listed below are necessary for its future operation:

1) Tighten axle load limits;

2) Prevent slow speed trucks passing through the bridge;

3) Periodically inspect the pavements and seal the cracks when found.

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江阴大桥桥面铺装裂缝分析

程 刚　陈先华　王 晓

(东南大学交通学院,南京 210096)

摘要:通过对江阴大桥浇注式沥青铺装4年的现场调查与跟踪,研究了浇注式沥青铺装的开裂原因.根据裂缝长度与宽度对其进行了总结以得到裂缝的发展规律.为评估交通荷载对铺装层的影响,同时进行了包括交通量、轴重、车速等调查.对现场取回的试样分别进行了拉拔试验与疲劳试验以评估铺装层的真实状况.结果表明:铺装层的疲劳抗力与高温稳定性不足、层间粘结层较弱、低速超载的大交通等是导致铺装层开裂的主要原因.

关键词:悬索钢桥;江阴大桥;正交异性桥面板;桥面铺装;浇注式沥青;开裂

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