

CRACKING OF THE ASPHALT SURFACING OF THE LONGEST SUSPENSION STEEL BRIDGE IN CHINA

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ABSTRACT

Due to its good flexibility, crack resistance and imperviousness to water, mastic asphalt is believed to be a suitable surfacing material for orthotropic steel deck plates of long-spanned steel bridges. It is widely and successfully used as an asphalt surfacing for long-spanned steel bridges in Europe and Japan. Jiangyin Bridge in China, one of the longest suspension orthotropic steel bridges in the world, is also paved with mastic asphalt. Severe cracks and ruts in its asphalt surfacing were observed during its early period of operation. Timely investigation into the premature damage of bridge deck pavements is necessary, not only for rehabilitation purposes, but also for the continued operation and maintenance of the rehabilitated surfacing system of this bridge and other steel bridges. This paper summarises the findings of four years of inspection on 41 550 m² of mastic asphalt surfacing on the orthotropic steel deck of Jiangyin Bridge and investigations into the cracks. The cracks are believed to be induced by rutting and fatigue. Lack of fatigue resistance, poor bonding to the steel deck and insufficient high-temperature stability appear to be the main reasons for the problems with the surfacing, besides high traffic volumes at low speed and excessively overloaded trucks.

Keywords: Cracking, Asphalt Surfacing, Orthotropic Steel Deck Plate, Jiangyin Bridge

1. INTRODUCTION

Jiangyin Bridge is one of the longest-spanned suspension steel bridges in the world. The steel box girder is 37.5 m in width with three lanes in each direction. The orthotropic deck plate consists of a 12-mm-thick plate stiffened by 6 mm × 300 mm × 280 mm longitudinal trapezoidal ribs and 10-mm-thick transverse diaphragms spaced at 3 200 mm. A mastic asphalt surfacing (Deng Xuejun, 2000) is laid directly on the steel deck plate, previously treated with an adhesive primer and rubberised bitumen underlayer, as shown in Figure 1. It is the first application of mastic asphalt on an orthotropic steel bridge deck in China. This paper summarises the findings of four years of inspection on 41 550 m² of mastic asphalt surfacing on the orthotropic steel deck of Jiangyin Bridge and investigations into the cracks.

The asphalt surfacing of Jiangyin Bridge has suffered from severe cracks and rutting since the early days of its operation. Timely investigation into the premature damage of deck pavements is necessary not only for rehabilitation purposes, but also for the operation and maintenance of the rehabilitated surfacing system of this bridge and other steel bridges. In order to explore the causes of this premature damage and to make proposals for the future renewal of the whole system (Huang Wei *et al.*, 2003), inspections have been regularly carried out since cracks were first observed. Traffic surveys, including traffic volumes, axle loads and vehicle speeds were also conducted.

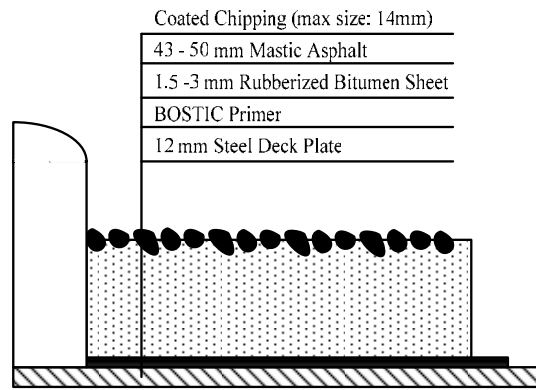


Figure 1. Asphalt surfacing on the steel deck plate of Jiangyin Bridge.

Samples from the rehabilitation project were tested by means of the wheel test, pull-out test and fatigue test. It was concluded from the investigation that the surfacing system's lack of high-temperature stability and fatigue resistance, insufficient bonding strength, and the high density of low-speed, excessively overloaded vehicles are the main causes of premature cracking in this case. With water permeating along cracks into the intermediate layer, the mastic asphalt lost the strength of its bonding to the steel deck, which led to failure of the surfacing system. An alternative surfacing system was proposed and applied to the severely damaged section of the girder. The system seems to be successful as no cracking was found after one year of operation.

2. CRACKS AND THEIR PROPAGATION

Longitudinal hairline cracks were observed in the surface over the webs of the ribs several weeks after the bridge was first opened, as shown in Figure 2a. During the first winter, transverse cracks were also found over the webs of the diaphragms and deck, as shown in Figure 2b. The longitudinal cracks were 0.5 to 2 m long and 0.3 to 1 mm wide, while the transverse cracks were about 0.2 to 0.3 m long. A few transverse cracks were also observed in the centre lane.

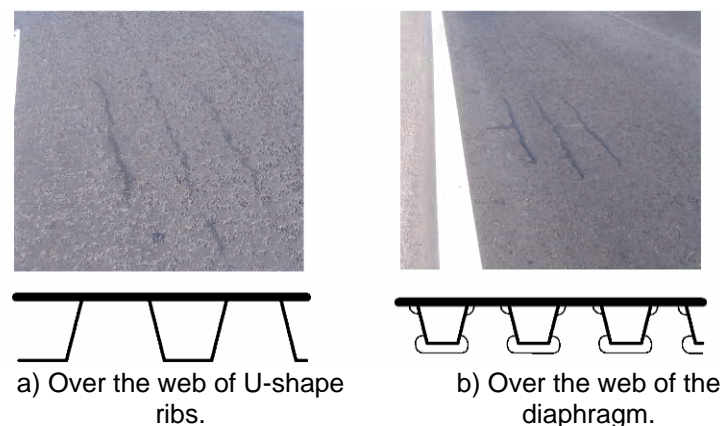


Figure 2. Surface cracks in mastic asphalt in the winter of 1999.

Further longitudinal cracks occurred 50 – 80 mm next to the former ones a year later, as shown in Figure 3. The length of these longitudinal cracks increased to 3 – 5 m, with a maximum cracking width of up to 2 mm. The pavement on both the inside and centre lanes was found to be cracked.

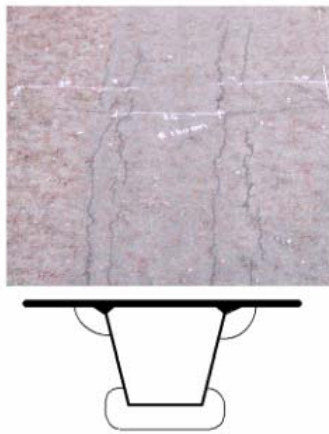


Figure 3. Longitudinal parallel cracks with transverse cracks (November 2001).

In the winter of 2002, the pavements under the wheel tracks of the inside lanes were found to be cracked almost transversely at a spacing of 3 200 mm, while in the centre lanes, the pavements over half the diaphragms were found to be cracked as well. Most of the longitudinal cracks in the southbound lanes were longer than 20 m, and the widest crack was about 5 –6 mm. The transverse cracks developed to a length of 600 – 700 mm.

In January 2003, the transverse cracks were found to have extended to 700 – 1400 mm; the average width reached 3 – 4 mm and the largest crack was close to 10 mm. The longitudinal cracks were shaped like fish-bones, and soon propagated into net cracks. Splitting and sliding occurred, with the width of the cracks being 40 mm at most. The system failed two months later because of severe delamination, sliding and displacement.

3. PLAN OF INVESTIGATION AND RESULTS

3.1 Laboratory Tests

The flexural fatigue test was conducted to determine the fatigue resistance and dissipated energy of the mastic asphalt, as shown in Figure 4. The composite beam is composed of a 12-mm steel deck and 50 mm of mastic asphalt, with an intermediate rubberised asphalt membrane, which was sampled in the rehabilitation project. Two samples were tested at room temperature. A 10 Hz sinusoidal load with an amplitude of 6 kN was selected to simulate an axle load of 130 kN passing over the bridge deck. The average fatigue life is 1.5 million, with a dynamic deflection of 0.25 mm before failure.

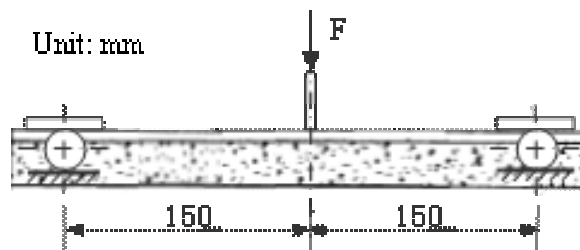


Figure 4. Fatigue test on composite beam.

The ‘pull-out’ test was conducted at room temperature (see Figure 5). The loading rate was about 200 N/s. Eccentricity should be avoided. Seven cores were drilled and tested. The bonding strength between the mastic asphalt and the steel deck plate was 1.01 MPa, with a maximum of 1.56 MPa and a minimum of 0.71 MPa.

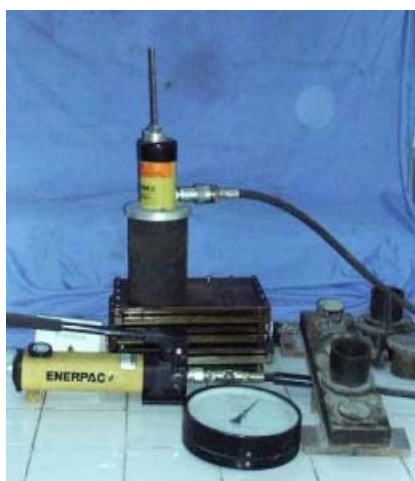


Figure 5. 'Pull-out' test equipment and samples.

3.2 Traffic Survey

Traffic surveys were conducted several times and included traffic volumes, traffic composition, traffic distribution, axle weight and the operating speed of trucks. Only trucks were counted. All trucks were classified into four types, according to the number of axles.

The traffic volume was based on data provided by the Jiangyin Bridge toll stations. The accumulated number of trucks that have passed over the Bridge since its opening day is up to 9 million, which is nearly half of the traffic volume. The traffic composition of the various classes of trucks is the percentage of the total trucks calculated according to the traffic volume data, as shown in Table 1.

Table 1. Traffic composition of trucks.

Truck type	Number of axles				Total
	Two	Three	Four	Five or more	
Percentage	64.23	32.48	3.04	0.25	100

A field traffic survey was conducted to obtain a clear picture of the traffic distribution. The survey lasted 72 hours and in total 12 000 trucks were recorded passing over the Bridge to Jiangyin. Almost 60% of the trucks were driving in the inside lane. The truck traffic distribution in the inside lane is calculated from the field survey data as a percentage for each type, as shown in Table 2.

Table 2. Truck composition and distribution in the southbound inside lane.

Truck type	Number of axles				Total
	Two	Three	Four	Five and more	
Composition (%)	52.06	10.18	36.73	1.04	100
Distribution (%)	46.87	72.15	82.03	91.67	--

The axle loads were measured with an axle weight sensor by means of random sampling in April 2001. The survey lasted 48 hours and in total 263 trucks were inspected. The results are given in Table 3.

Table 3. Mass per rear axle of heavy trucks.

Mass per rear axle(kN)	Percentage of its own type			
	Two	Three	Four	Five and more
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
More than 150	0.77	3.03	24.44	0.00

The speeds of the trucks travelling in the southbound inside lane were measured with a radar speed detector on 20 February 2001, as shown in Figure 6. Trucks travelling at a speed lower than 40 km/h made up 70% of the total of 127 trucks.

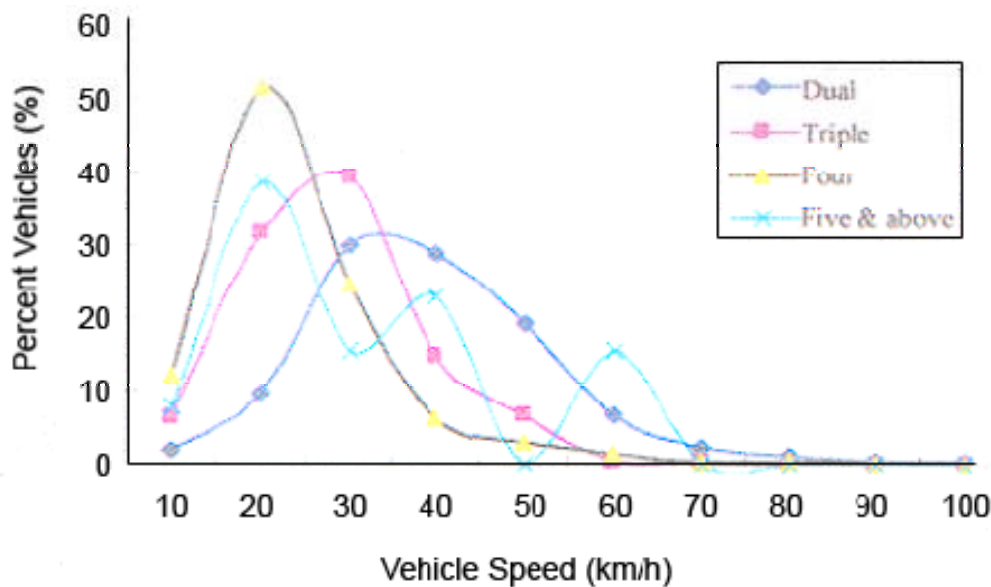


Figure 6. Speed of trucks travelling in the inside lane to Jiangyin.

4. ANALYSIS AND DISCUSSION

4.1 Properties of the Mastic Asphalt Surface System

4.1.1 High-Temperature Properties

Mastic asphalt designed in accordance with BS2000 does not meet the high-temperature requirements of the Chinese criterion (Deng Xuejun *et al.*, 2000). The wheel track test under different temperatures (Zhang Lei, 2004) shows that dynamic stability of the mastic asphalt used at Jiangyin Bridge is highly susceptible to temperature. When the temperature increases from 45°C to 60°C, the dynamic stability falls sharply from 1 305 to 303. According to on-site temperature observations of the deck pavement, days when the pavement temperature is over 60°C amount to almost 30% of the whole summer, which means inevitable ruts and plastic deformation (Zhang Lei, 2004) in a hot summer.

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

The bonding and waterproofing system of Jiangyin Bridge was composed of a solvent bond primer named BOSTIC and a 1.5 – 3 mm sheet of rubberised bitumen blend. The rubberised bitumen blend was combined with 75% Caribit 45 supplied by the Shell Company and 25% calcareous mineral filler from the UK. The presence of the blend raised the asphalt content of the whole asphalt surfacing system, thus to some extent decreasing its high-temperature stability.

4.1.2 Fatigue Resistance of Mastic Asphalt

As the high-temperature stability of mastic asphalt could not reach the lowest requirement of the Chinese Standard, the TLA and coarse aggregate contents were increased and the soluble asphalt content was decreased from 8.25% to 7.5% to improve its stability (Deng Xuejun *et al.*, 2000). This did indeed increase the high-temperature stability of the mastic asphalt as its dynamic stability increased from 121 to 303, and its Marshall stability at a flow value of 5 mm increased from 6.4 kN to 7.8 kN (Deng Xuejun *et al.*, 2000). However, fatigue tests on samples from the rehabilitation project have indicated that too much TLA may have a bad effect on crack and fatigue resistance, although it can certainly improve the high-temperature stability, aging resistance and durability of the mixture. The fatigue life of mastic asphalt under 6 kN is only 1.5 million cycles, which is far lower than the 12 million cycles required by the similar Runyang suspension bridge (Chen Xianhua, 2003). Therefore, the poor fatigue properties of mastic asphalt surfacing are a significant cause of premature cracking.

4.1.3 Efficiency of Bonding and the Waterproofing Membrane

Insufficient adhesion or shear strength may lead to slippage and delamination. It may also induce the laceration and 'squeezing' of asphalt surfacing, as was observed in the asphalt surfacing of Haicang Bridge and Junshan Bridge (Zhang Lei, 2004).

The adhesive strength between mastic asphalt and a steel deck plate is 0.71 – 1.28 MPa. The strength decreases with increasing temperature or with the penetration of water into the bottom of the wearing course through cracks. The theoretical shear stress between mastic asphalt and a deck plate under the most adverse conditions is up to 0.68 MPa (Huang Wei, 2003). Insufficient adhesion therefore accelerated the destruction of the mastic asphalt surfacing in the west outside lane.

4.2 Analysis of Operating Conditions

4.2.1 Mechanical Conditions

Firstly, the cracking of an asphalt surfacing on an orthotropic steel deck is related mainly to local negative moment (Chen Xianhua, 2003; Huang Wei *et al.*, 2003; Gu Xinyu *et al.*, 2002). Transverse tensile stress, which causes longitudinal cracks perpendicular to the stress, occurs at the top of the pavement over webs of U-shaped ribs adjacent to the wheel load. Longitudinal tensile stress, which induces transverse cracks perpendicular to the stress, occurs at the top of the pavement over webs of diaphragms close to the wheel load (Chen Xianhua, 2003; Huang Wei *et al.*, 2003; Gu Xinyu *et al.*, 2002). Observations of the premature cracks confirmed these mechanisms.

Secondly, unbalanced traffic in two directions may play some role in damaging mastic asphalt. As the survey revealed, there were far more heavy trucks in the southbound lanes than in the northbound lanes, and moreover most heavy trucks in the southbound were travelling in the inside lane. Thus, the unbalanced conditions may have increased the torsion. Furthermore, shaking and buffeting of the long-spanned suspension steel bridge may also have bad effects on the bonding layer and wearing course.

4.2.2 Traffic Conditions

- Heavy-Duty and Overloaded Traffic

3D-FEA was employed to calculate the responses of the steel deck plate surfacing system under overloaded trucks. The calculated results are listed in Table 4. Axle load reduction based on equivalent fatigue damage (Liu Zhengqing, 2004) was used to analyse the effects of overloading. The fatigue damage caused by an overload of 30% is six times that of a standard axle load of BZZ-100, an overload of 50% is equivalent to 32 times, and an overload of 100% up to 93 times. To draw a conclusion, overloaded trucks increased the flexural fatigue damage of the asphalt surfacing system tremendously.

Table 4. Influences on the strain of asphalt surfacing with overloaded trucks.

Overloading Ratio	Negative(1×10^{-6})			Positive(1×10^{-6})		
	ϵ_x	ϵ_y	ϵ_z	ϵ_x	ϵ_y	ϵ_z
00%	-817	-728	-292	444	535	80
30%	-1070	-793	-315	578	659	109
55%	-1281	-875	-387	693	789	131

Equivalent Single Axle Loads (ESALs) of BZZ-100 were calculated based on the work of Liu Zhengqing (2004) and are shown in Table 4. The total ESALs passing over the southbound inside lane by the end of 2002 was about 15 million, which is far beyond the fatigue life of the pavement. Accordingly, heavy traffic and overloaded trucks are the most important causes of the damage.

- Slow Speed of Trucks

Laboratory tests have revealed that mastic asphalt is susceptible to temperature and loading speed. The creep rate increases quickly with temperature (Zhang Lei, 2004). The energy dissipated per cycle decreases with higher loading frequency, as shown in Figure 7. High dissipated energy per cycle means severe damage to materials. Slow-moving vehicles therefore have some adverse effects on the permanent deformation and fatigue resistance of mastic asphalt.

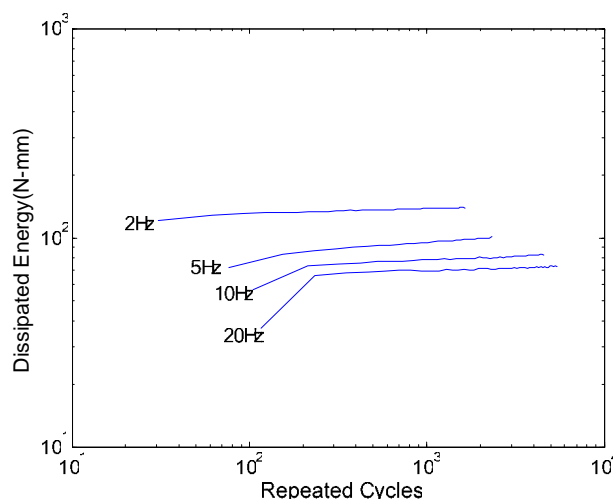


Figure 7. Dissipated energy of composite beam at different frequencies.

4.3 Other Causes

The southern approach to Jianguyin Bridge has a 2-km-long slope with an inclination of 3%. In addition, the main beam declines by 2% over a slope of 700 m. The combination of a very long upwards slope and overloading lowers the speed of heavy trucks. This may

explain why the damage to the deck plate surfacing in the southern direction is more severe than that in the northern direction.

During its operation, timely but efficient maintenance could prevent water intrusion and retard the damage to the bridge. Without reliable maintenance, water or moisture could infiltrate into the bottom of the waterproofing membrane and weaken the adhesion between the mastic asphalt and the deck plate. Cracking develops quickly once pavements their lose bonding strength and failure could occur as a result in large areas of the deck plate surfacing.

5. CONCLUSION

This paper has summarised the findings of four years of inspection on the mastic asphalt surfacing system of Jiangyin Bridge. Rut-induced cracks and fatigue cracks were evidence of major premature deterioration of the mastic asphalt surfacing. Lack of high-temperature stability and fatigue resistance, inefficient adhesion, overloaded trucks travelling at slow speeds, dense and heavy-duty traffic were the key factors leading to this deterioration.

It is necessary for road engineers to evaluate the situation with regard to local climate and traffic accurately, and to choose suitable test methods and technical norms before paving the surface system.

Regarding Jiangyin Bridge, the precautions listed below are necessary for its future operation:

- Enforce axle load limits more strictly.
- Prevent trucks from travelling over the bridge at slow speeds.
- Periodically inspect the pavement and seal the cracks when found.
- Keep the pavement cool enough during hot summers.

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