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Condition survey and analysis of epoxy asphalt concrete pavement on Second Nanjing Yangtze River Bridge: a ten-year review

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Abstract: To obtain a complete picture of the epoxy asphalt pavement condition on the Second Nanjing Yangtze River Bridge, an on-site survey is conducted to collect information regarding traffic composition and extents of pavement distresses. The survey shows that 30 m^2 out of the entire 3.8×10^4 m^2 pavement exhibits potholes and alligator cracks. Other surface cracks are also found, including regular longitudinal cracks, short hairline cracks, bubble cracks, and ring cracks. Rutting and shoving are not observed on the pavement. The causes of pavement distresses are discussed by analyzing the pavement mechanical response with actual traffic composition. Research results indicate that the regular longitudinal cracks occurring at ribs near wheelpaths are due to fatigue damage. Short hair cracking and bubble cracking are mainly related to construction defects. Alligator cracks are the results of the development of regular, short hair and bubble cracks lacking effective maintenance. Potholes are induced by the cracking and moisture ingression.

Key words: steel bridge; orthotropic decks; cracking; pothole; survey

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Since the beginning of widespread construction of orthotropic steel deck bridges in China in 1990s, most of these bridges have experienced serious premature failure problems in the deck pavement[1-2]. With frequent overloading and high deck temperatures (up to 70 ℃) during prolonged summers, cracking, rutting, and shoving were observed on bridges that had used polymer modified asphalt, stone mastic asphalt (SMA), or Gussasphalt for deck surfacing, including many long-span bridges such as the Humen Cable-Stayed Bridge (main span 888 m)[3] and the Jiangyin Suspension Bridge (main span 1 385 m)[4-6].

To solve the early pavement failure problems on orthotropic steel deck bridges, a new material, epoxy asphalt, was introduced from the USA and first applied on the Second Nanjing Yangtze River Bridge (SNYRB) by SNYRB Construction Headquarters and Southeast University. SNYRB is a 1 238 m long cable-stayed bridge, consisting of a 628 m center span, two 246. 5 m side spans, and two 58. 5 m flanking spans. The center span is the longest among all cable-stayed bridges in China when the bridge was completed in 2001. The bridge deck is 37. 2 m wide and carries six lanes of traffic, with a 2. 8% longitudinal slope and a 2% transverse slope from the centerline of the bridge. The total deck area paved with epoxy asphalt concrete is about 3.8×10^4 m^2[7].

Before construction of the deck pavement, a research project was initiated and completed to optimize the mixture and structural designs. The performance of the epoxy asphalt mixture was evaluated extensively in the laboratory, with the optimized mixture design showing a Marshall strength of 56. 6 kN, a dynamic stability of 20 137 cycles/mm at 70 ℃, a −28. 4 ℃ fracture temperature, and a 90. 8% tensile strength ratio[8-9]. The final pavement structural design for the SNYRB is 50 mm epoxy asphalt concrete, consisting of two 25 mm lifts with an epoxy asphalt bond coat in between[2, 8]. This pavement structure is designed for a minimum service life of 15 years, or 12 million equivalent single axle loads, and a pavement temperature range of −15 to 70 ℃, based on the actual traffic and weather conditions[2]. The research project concluded that the epoxy asphalt concrete pavement placed on the SNYRB would show good resistance to rutting, moisture, and fatigue damage. To ensure the success of this new paving material and design, extreme care was taken during the construction to minimize construction related risks, including efforts such as manual picking and screening of aggregate particles to the right sizes and full coverall on workers to prevent sweat and dust contaminations onto the steel deck.

After being opened to traffic in 2001, the deck pavement did exhibit superior performance compared with other types of asphalt mixtures used on other bridges. This spurred a wide application of epoxy asphalt for paving orthotropic steel deck bridges constructed thereafter in China, and currently it is still the case. After being in service for ten years, however, the deck pavement on the SNYRB has also been showing a variety of distresses. It is imperative to fully evaluate the conditions of the epoxy asphalt concrete pavement on the SNYRB, and to investigate potential causes of distresses. With actual traffic and climate data collected over the past ten years, it is also an appropriate time to re-evaluate the validity of the original steel deck pavement design and to recommend improvements to the design procedure and necessary maintenance activities for keeping the deck pavement in good condition.

1 Objective

This paper evaluates the condition of epoxy asphalt concrete pavement on the SNYRB after having been in service for 10 years. The types of pavement distresses are classified, and the causes of each type of distress are discussed. The objective is to provide appropriate maintenance recommendations for extending the service life of epoxy asphalt

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concrete pavements on orthotropic steel deck bridges.

2 Classification of the Pavement Distress

A condition survey of epoxy asphalt pavement on the SNYRB was conducted. The results, as illustrated in Fig. 1, show that the pavement on the two fast lanes is in good condition. The pavement on the northbound drive lane has some longitudinal regular cracks and short hairline cracks, while the pavement on the two slow lanes has potholes and irregular cracks including bubble cracks, ring cracks and alligator cracks. It is encouraging that no shoving or rutting distress was found on the entire epoxy asphalt pavement.

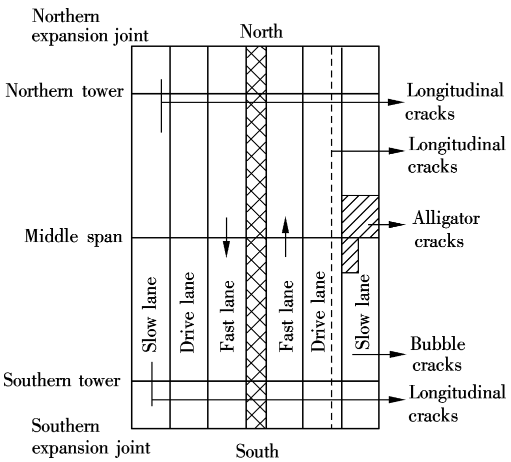


Fig. 1 Types and distribution of pavement distresses on SNYRB

Among all the pavement distresses, about 95% of them were observed on the two slow lanes, with 85% of the distresses occurring on the northbound slow lane, and 10% occurring on the southbound slow lane.

2.1 Regular cracks

A regular crack is defined as a crack that is mostly caused by structural damage or thermal stress, and propagates longitudinally or transversely. Field investigation of the SNYRB pavement shows that regular longitudinal cracks occurred along the positions of deck stiffening ribs or girders, or in the truck wheel paths. One longitudinal crack was found crossing the whole bridge on top of one stiffening rib in the northbound drive lane, as shown in Fig. 2. Through the observation and investigation, the longitudinal crack was located upon the fatigue damage joint between the rib and deck. In the southbound slow lane, two longitudinal cracks were also observed, one in the center of the lane, and the other in the right wheel path, as shown in Fig. 3.

Fig. 2 Longitudinal regular cracks in the northbound drive lane on SNYRB

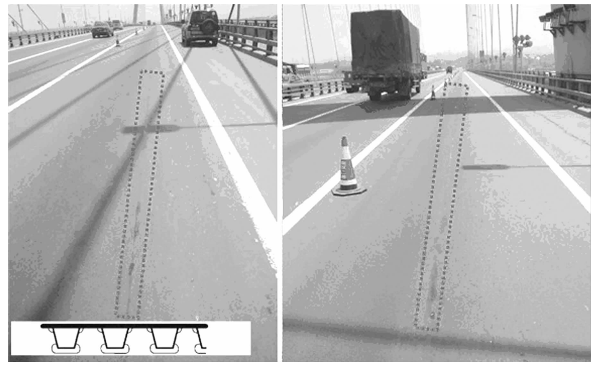


Fig. 3 Longitudinal regular cracks in the southbound slow lane on SNYRB

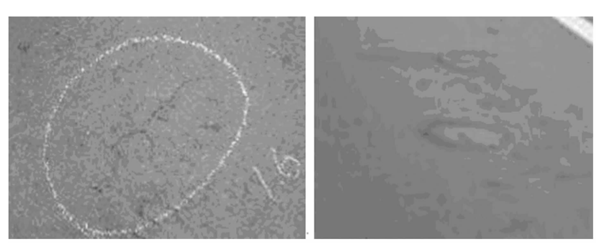
2.2 Short hairline crack

Short hairline cracks are defined as cracks with irregular shapes, a length less than 30 cm, a width less than 0.2 cm, and a depth less than 2 cm, as illustrated in Fig. 4. Short hairline cracks are mostly observed at the surface of epoxy asphalt pavement on steel bridges. On-site survey on the SNYRB reveals that the pavement in the northbound slow lane had dozens of short hairline cracks, most of which were located in the left wheel path from the southern expansion joint to the southern tower.

Fig. 4 Short hairline cracks in the northbound slow lane on SNYRB

2.3 Bubble and ring cracks

Bubble cracks are characterized with short radial cracks of about 15 cm in length in at least three directions, as shown in Fig. 5(a). Ring cracks shown in Fig. 5(b) appear around the radial cracks due to repeated wheel loading and dynamic water pressure. Based on the on-site investigation on the SNYRB, most of the bubble and ring cracks occurred in both the northbound slow lane and the northbound drive lane.



(a) (b)

Fig. 5 Bubble and ring cracks in epoxy asphalt pavement on SNYRB. (a) Bubble crack; (b) Ring cracks

2.4 Alligator cracks

Some alligator cracks are found in the pavement on the SNYRB. The most serious alligator crack was located in the northbound slow lane at the span center of the bridge, the area of which was 20 m^2, as shown in Fig. 6.

Fig. 6 Alligator crack in the northbound slow lane on SNYRB

Another serious alligator crack occurred in the southbound slow lane at the span center between the southern tower and the southern expansion joint. As shown in Fig. 7, this alligator crack is also in the right wheel path.

Fig. 7 Alligator crack in the southbound slow lane on SNYRB

2.5 Potholes and rusts of steel deck

Potholes are developed from cracks under the coupling action of wheel loading and dynamic water pressure if the cracks are not sealed or patched in time. Long-term observation of epoxy asphalt pavement on the SNYRB shows that a pothole first occurred in the pavement in the form as shown in Fig. 8(a). Two potholes were found in the pavement on the northbound slow lane, and had been patched by the maintenance crew of the bridge maintenance company. The distressed area is about 0.2 m^2 for one pothole, and about 2 m^2 for the other, as shown in Fig. 8(b). Moisture was trapped inside the potholes during the patching process, which later caused corrosion of the steel deck, as shown in Fig. 9.

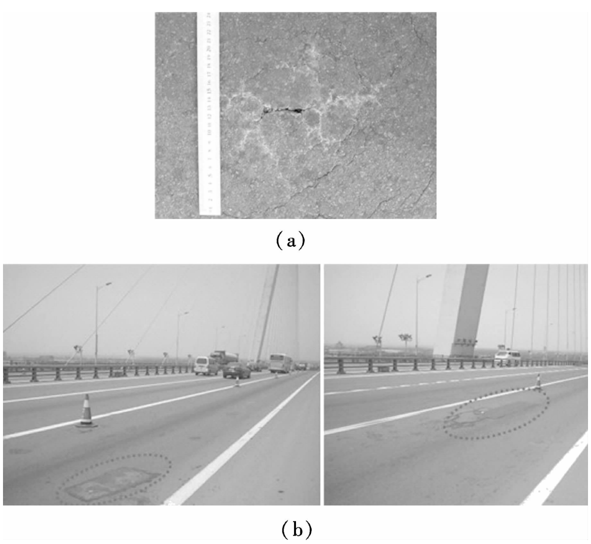


Fig. 8 Pothole in epoxy asphalt pavement on SNYRB. (a) Small pothole; (b) Patched pavement for two potholes

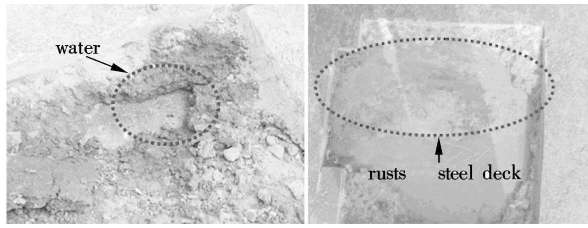


Fig. 9 Water remaining in the pavement and rust of the steel deck on NSYSB

2.6 Accident distress (scratching)

Other than the common pavement distresses above, accident distress was also found on the pavement on the SNYRB. A few scratches caused by the striking of falling objects from vehicles were observed in the slow lanes, as shown in Fig. 10.

Fig. 10 Scratching on epoxy asphalt pavement on SNYRB

3 Discussion on the Causes of Pavement Distress on SNYRB

3.1 Effects of traffic conditions

With the assistance from SNYRB Co, Ltd., the traffic conditions including traffic volume, truck percentage, and truck tire pressure were investigated. The annual traffic volume since the bridge was opened to traffic is listed in Fig. 11. As can be seen, the annual traffic volume keeps increasing with time. The daily average traffic volume achieved a value of 59 549 in 2010, which exceeded the original design traffic volume of 41 951 vehicles per day[2].

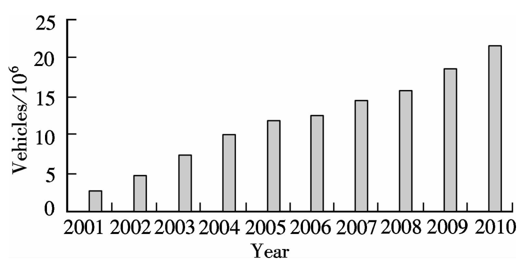


Fig. 11 Annual traffic volume on SNYRB

To estimate the truck traffic composition, a 24 h field traffic survey was conducted in the southbound direction on the bridge, where almost 85% of the pavement distresses occurred. The survey also shows that all the trucks were driving on either the slow lane or the drive lane, and about 60% of the trucks or 90% of the trucks with more than two axles were driving on the slow lane. It can be concluded that truck traffic, especially heavy truck traffic, is one main factor contributing to pavement distresses, since the fast lane, which had received no truck traffic, showed little distress, while the slow lane, which had received most heavy truck traffic, showed most serious distresses.

3.2 Mechanistic analysis for regular crack

Regular cracks are mostly fatigue cracks caused by repeated traffic loading. To investigate the mechanism of the initiation of regular cracks, a three-dimensional (3D) finite element model of epoxy asphalt pavement on a local orthotropic steel deck is established using the commercial software ADINA. An 8-node 3D solid element is selected to model the asphalt pavement and a shell element is used to model the steel bridge deck. Between the shell and solid elements, rigid links are adopted to make the pavement and steel deck deform together. A sensitivity analysis of stress response is then conducted to determine the FE mesh size by reducing the size of the element gradually till the difference of the calculated stresses in two processes is within 5%[10]. As a result, areas around the critical stress positions such as ribs are meshed with fine element sizes, while regions located far away from critical stress positions are meshed with coarse element sizes. The final FE model, as shown in Fig. 12, includes 12 756 elements. According to the survey results of tire pressure, a standard tire pressure of 0.7 MPa, a 60% overloading tire pressure of 1.1 MPa, and a maximum tire pressure of 1.38 MPa are selected for computation. The maximum strains in the pavement at various temperatures and tire pressures are shown in Fig. 12. The FEM simulation results listed in Tab. 1 show that the maximum pavement strain occurs at the pavement surface on top of a stiffener of the orthotropic deck, as represented by point A in Fig. 12.

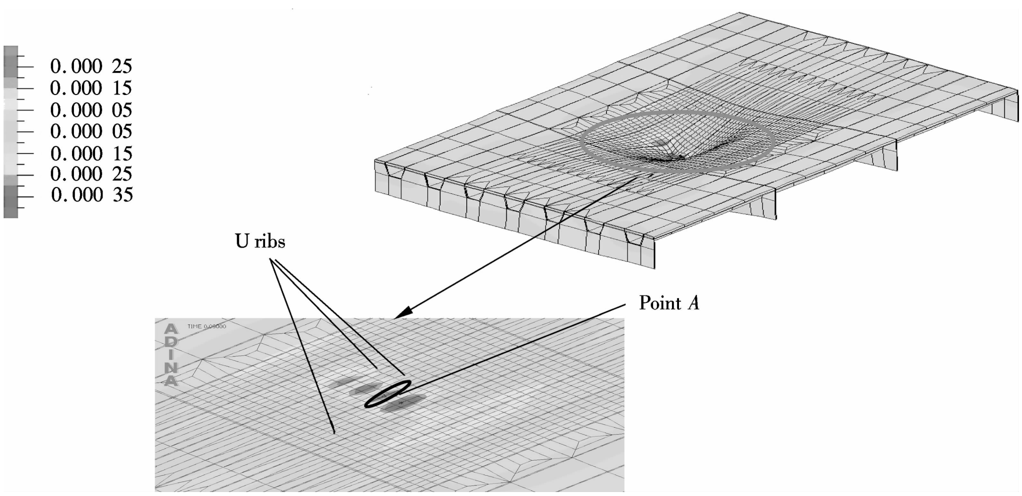


Fig. 12 3D FE model and local model for epoxy asphalt pavement on local orthotropic steel deck

Tab. 1 Maximum strain of pavement at different temperatures and type pressures 10^{-6}

Type pressure/MPa	Temperature/℃		
	10	20	30
0.70	198	326	624
1.10	308	507	971
1.38	387	637	1 218

3.3 Causes of non-regular cracks

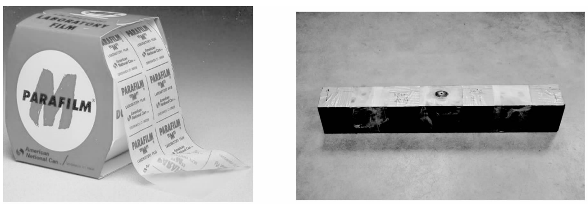
Short hairline cracks are typically caused by construction defects, and have nothing to do with asphalt mixture properties. If short hairline cracks are not sealed properly, they will develop into alligator cracks due to heavy traffic and environmental influences. The relationship between the initiation of short hairline cracks and the construction process needs further investigation to reduce the occurrence of this type of cracks.

Bubble cracks are caused by moisture introduced during the paving process. Sources of moisture include water dripping from bridge towers or cables, residual water on the deck after rain, and sweat from workers during paving. Such moisture contamination may exist on steel bridge decks paved with any type of asphalt mixture. However, it is interesting to observe that bubble cracks only occur in epoxy asphalt pavements, while they have not been observed on steel bridges paved with other asphalt mixtures, such as Gussasphalt (with zero air-void content), polymer modified asphalt mixtures and stone mastic asphalt mixtures (with low air-void content). The reason is that the epoxy asphalt mixture is mixed and placed at temperatures much lower than other asphalt mixtures so that epoxy resin can cure at a slower rate to ensure sufficient construction time. Typical mixing and compaction temperatures for epoxy asphalt are around 120 and 110 ℃, respectively. Such temperatures cannot guarantee complete evaporation of moisture residuals on the steel deck before the epoxy asphalt is placed and completely compacted. Therefore, moisture contamination should be strictly forbidden during the construction process of epoxy asphalt pavement.

Ring cracks always appear around bubble cracks due to repeated traffic loading and/or potential dynamic water pressure. If the non-regular cracks are not timely treated, alligator cracks will be finally formed.

3.4 Cause of potholes

If cracks are not sealed in time, water from rain or snow will infiltrate the pavement. Under the coupling action of heavy truck loading and dynamic water pressure, potholes will eventually develop. To verify the detrimental effect of moisture on epoxy asphalt performance such as resistance to fatigue cracking, a strain-controlled four-point beam fatigue test was conducted on specimens conditioned with moisture. Such a test was designed to simulate the coupling of moisture and loading on the deterioration of epoxy asphalt pavement. The preconditioning procedure for moisture treatment was determined as follows: a specimen was first saturated in water at 635-mm-Hg vacuum for 30 min and then placed in a 60 ℃ water bath for 24 h. After that, the specimen was cooled to 20 ℃ and wrapped with Parafilm M, a moisture-resistant, thermoplastic flexible plastic sheet, to retain its internal moisture. Moisture loss during the fatigue test can be controlled within 1 g by Parafilm M. Pictures of Parafilm M and a beam wrapped with it are shown in Fig. 13.



(a) (b)

Fig. 13 Parafilm M sheet and beam with moisture-conditioning. (a) Parafilm sheet; (b) Beam wrapped with sheet

The fatigue test was conducted in accordance to AASHTO T 321. Both dry and moisture conditioned specimens were tested for comparison. The air-void contents of all specimens were controlled under 3%, which was the same maximum value specified for the deck pavement on the SNYRB. Two test conditions, 600 microstrain at 10 ℃ and 900 microstrain at 20 ℃, and a 10 Hz sinusoidal loading wave were selected to evaluate the mixture performance. The test results show the fatigue life of a moisture conditioned specimen at 10 ℃ is 169 182 cycles, which is about 1/6 of the fatigue life of 1 030 091 cycles of a dry specimen. The fatigue life of a moisture conditioned specimen at 20 ℃ is 466 899 cycles, which is around 3/5 of the fatigue life of 789 104 cycles of a dry specimen. It clearly shows that moisture conditioning reduced the fatigue life of the epoxy asphalt mixture. Therefore, moisture related damage should be noticed and further investigated in a future study.

4 Conclusions

This paper presents the field survey results and analysis of causes of pavement distresses on the SNYRB. The following conclusions are obtained from the study:

1) After 10 years in service, most of the pavement on the SNYRB is still in good condition, except for a few longitudinal regular cracks, short hairline cracks, bubble cracks, ring cracks, alligator cracks and potholes appearing on the slow or drive lane. The area of the pavement with severe deterioration, such as potholes and alligator cracks, is about 30 m^2, which is a small area when compared with the 3.8×10^4 m^2 area of the entire epoxy asphalt pavement on the SNYRB. No shoving or rutting distress was observed on the bridge pavement.

2) Truck traffic is the main factor that contributes to the pavement distresses on the SNYRB. The pavement on the two fast lanes showed little distress due to the lack of truck traffic. Contrarily, about 95% of observed distresses were on the two slow lanes, which received the most truck traffic, especially heavy truck traffic.

3) Regular longitudinal cracks in the pavement generally occur along U ribs or stiffeners, where the maximum strain or stress in the pavement is located. Short hairline cracks are caused by construction defects. Bubble cracks are caused by moisture contamination from water dripping from towers or cables or from worker sweat during the paving process, and are unique distresses in epoxy asphalt pavement on steel bridge decks. At a later stage, ring cracks may appear around the bubble cracks. If the above cracks are not timely and properly sealed, serious distresses such as potholes and alligator cracks can develop from these cracks under the coupling action of repeated traffic loading and dynamic water pressure.

Moisture reduces the fatigue life of epoxy asphalt pavements. However, the effect of moisture on the forming mechanism of potholes should be further investigated in future studies.

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南京第二长江大桥环氧铺装服役状况调研与分析
——服役十年回顾

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摘要：为研究南京第二长江大桥环氧沥青混凝土铺装的服役性能，对其进行了现场调研与分析，包括铺装经受的交通量特征及铺装病害类型和程度等. 调研观测发现：在 3.8×10^4 m^2 的环氧铺装中，坑洞与龟裂等严重病害面积大约 30 m^2；铺装层裂缝可分为纵向裂缝、短裂缝、鼓包裂缝、圆形裂缝等；车辙和推移病害在南京二桥铺装中未出现. 根据现场调查的交通数据，采用力学仿真模型对不同类型铺装病害的发生机理进行分析. 分析结果显示：位于 U 肋肋顶、靠近轮迹带处的常规纵向裂缝是铺装疲劳损伤所致，短裂缝与鼓包裂缝由铺装施工缺陷所致. 裂缝未得到及时养护，演变成龟裂. 在行车荷载与动水压力的耦合作用下，龟裂演变成坑洞.

关键词：钢桥；正交异性板；裂缝；坑洞；调查

中图分类号：U418.6