Establishment and damage analysis for steel deck pavement composite beam fatigue model

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Abstract. Different from high-grade asphalt pavement, steel bridge thin layer pavement share traffic load with orthotropic steel deck pavement and its fatigue damage is related to the latter. Based on deformation characteristics of orthotropic steel deck pavement, we established a corresponding composite beam fatigue test model. Based on damage mechanics, we put up with a steel bridge composite beam fatigue damage model. Through steel deck pavement composite beam fatigue experiments, composite beam fatigue damage equation was established. Results show that the fatigue damage test model can well reflect local mechanics response of steel deck pavement; composite beam made of different paving materials have different damage rules: stiffening pavement system has the smallest fatigue damage rate, modified asphalt SMA has the biggest fatigue damage rate and epoxy asphalt concrete has a middle level.

1. Introduction
Steel bridges are widely used in China due to their light weight, stable structure and long-spanning ability[1~3]. These steel bridges generally use steel box girder or steel girder as the load-bearing beam and often adopt orthotropic plate, which is composed of vertical and horizontal stiffening rib and bridge panel, as bridge deck structure bearing wheel load. However, steel deck pavement on orthotropic steel deck is not ideally used [4~5].

With the in-depth study of steel deck pavement technology, people gradually realize the big difference between steel deck pavement and high-grade road asphalt pavement: steel deck pavement is not only about material, but is more likely to be related to the characteristics of orthotropic plate. Since orthotropic plate has different stiffness in some parts, bridge pavement bears a big pulling stress on the surface and a shear stress on the bottom. Tensile stress is likely to cause fatigue cracks of the pavement and shear stress will cause delamination, which changes the stress state of pavement, and intensifies the generation and expansion of fatigue cracks[6~7]

As for the study of bridge deck pavement, Southeast University analyzed the orthotropic bridge pavement with simplified support structure and studied stress-strain fields of orthotropic steel bridge paved layer at different load positions. According to the elastic layer theory of rigid support, Xiao Qiuming from Changsha University of Science and Technology analyzed shear stress of gussasphalt mixture steel deck pavement and steel box girder when the car moves and brakes emergently. Based on the splitting fatigue test and composite beam fatigue test, Liu Zhenqing had a regression analysis
and put up with the fatigue equation of pavement structure. By analyzing the result of beam bending fatigue test with an energy consume method, Min Zhaohui derived fatigue damage evolution equation and fatigue life prediction formula for epoxy gussasphalt pavement.

At present, as for the research of steel bridge deck pavement fatigue, orthotropic plate and bridge deck pavement are often separated from each other and studied separately, thus ignoring their interaction in the process of fatigue. Only by combining them together, can fatigue characteristics of steel deck pavement structure be stated clearly (Zhang, 2013).

2. Fatigue damage model of beam

2.1. Test model of steel deck pavement composite beam

Orthotropic steel deck pavement and normal asphalt mixture pavement have different structures. As the only part connecting the car body and pavement, tires contact with pavement surface in a certain area and under a certain vertical load. Since steel box girder surface is orthotropic, the trapezoidal stiffening rib on the bottom will cause quite obvious stress or strain for upper pavement. Therefore, test model of steel deck pavement composite beam is made according to point A model, which is shown in figure 1:

![Composite beam test model based on deformation characteristics of orthotropic steel deck pavement.](image)

Based on the simplified steel deck pavement model, steel deck pavement test model was designed, step loading was done and the corresponding vertical displacement was tested. At the same time, finite element analysis model of steel box girder and test model was established, the maximum displacement of stiffeners top was calculated and it was compared with measured displacement. Please refer to figure 2:
From the figures, it can been concluded that the analysis results of two finite element models change with loads and that the maximum tensile stress of steel deck pavement composite beam test model is very close to measured results. Therefore, it can be concluded that three-point composite beam model can well reflect the actual bridge deformation characteristics of orthotropic steel deck pavement.

2.2. Fatigue damage model of steel deck pavement composite beam

2.2.1. Composite beam flexural rigidity equivalent calculation

In accordance with flexural rigidity equivalent simplification principle, the steel deck pavement thickness should be simplified as gussasphalt paved layer equivalent thickness. The total flexural rigidity of simplified rectangular beam is equal to the total flexural rigidity of gussasphalt paved layer, steel deck pavement and cross-sectional axial force flexural rigidity. That is to say, calculation formula for simplified gussasphalt paved layer rectangular beam total flexural rigidity is:

$$K = \frac{E_s H^3}{12(1-\mu_1^2)}$$

The total height of simplified gussasphalt paved layer rectangular beam, H, can be calculated by substituting the corresponding modulus, thickness and poisson's ratio of gussasphalt paved layer and steel deck.

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**Figure 2.** The maximum vertical displacements corresponding to loads.

**Figure 3.** The maximum tensile strain corresponding to loads.
In the formula, $K$—simplified gussasphalt paved layer rectangular beam total flexural rigidity; $H$—total height of simplified gussasphalt paved layer rectangular beam; $h_1$—gussasphalt paved layer thickness; $E_1$—gussasphalt paved layer modulus; $\mu_1$—gussasphalt paved layer poisson's ratio; $h_2$—steel deck thickness; $E_2$—steel deck modulus; $\mu_2$—steel deck poisson's ratio; $n_1$—steel deck modulus to gussasphalt paved layer modulus ratio, that's $n_1 = E_2/E_1$; $\kappa_u$—binding coefficient between steel deck and gussasphalt paved layer, $\kappa_u = 0$ means fully slipping and $\kappa_u = 1$ means fully bonding.

2.2.2. Composite structure damage calculation based on damage mechanics
Materials under alternating load suffer increasing internal defects. The process during which damage accumulates constantly until mechanical properties of material loss is called fatigue. The variable which represents damage changing process in damage mechanics is called damage variable. In the development of damage mechanics, damage variable has a variety of definitions: effective area after damage to effective area in initial undamaged condition ratio, elastic modulus in loading process to elastic modulus before loading ratio, stress after damage to stress in initial condition ratio.

Damage variable, $D$, is defined according to steel deck gussasphalt pavement composite beam structure system.

$$D_x = \frac{E_x - E_0}{E_0} \quad (3)$$

In the formula, $D_x$—damage variable of composite beam structure system during the $x$th fatigue process; $E_x$—elastic modulus of composite beam structure system during the $x$th fatigue process; $E_0$—initial elastic modulus of composite beam structure system.

According to the composite test model established in the last section and based on orthotropic steel deck deformation characteristics, elastic modulus of composite beam structure system, $E$, can be calculated by the following formula.

$$E = \frac{\sigma}{\epsilon} = \frac{3lP}{2bh^2} \frac{H/l^2}{d} \quad (4)$$

In the formula, $H$—beam height; $l$—beam span; $d$—beam bottom deflection; $b$—composite beam width; $P$—load.

Initial strain $\epsilon_{(0)}$ is determined by measured beam bottom deflection $d_{(0)}$ when cyclic loading appears for the first time in fatigue experiment.

3. Steel deck composite beam of typical pavement material fatigue experiment and result

3.1. Raw materials and technical index
In this paper, SK (South Korea) bitumen was used as basis bitumen. Gussasphalt adopt polymer compound modified asphalt, with a penetration of 31.8 ($25^\circ C, 0.1mm$), softening point of 90.5$^\circ C$, and 5$^\circ C$ ductility of 28.6cm. Epoxy asphalt binders are made of Japanese TAF epoxy resin.

Coarse aggregates adopt basalt. Fine aggregates adopt limestone. Mineral powders adopt limestone. All performance indexes can meet the highest requirement of current industry standard.

In accordance with Highway Engineering Asphalt and Asphalt Mixture Experiment Procedures (JTG E20-2011) and Highway Steel Box Girder Pavement Design and Construction Technology
Guide, the best bitumen aggregate ratio of GA10, SMA10 and EA10 is determined and basic performance test is done (Chen et al., 2011). Please refer to Table 1 [8–9].

| Kind of asphalt mixture | GA10 | SMA10 | EA10 | Experiment method |
|-------------------------|------|-------|------|-------------------|
| Best bitumen aggregate ratio / % | 7.8  | 6.3   | 6.5  | JTG F20-2011 T0705 |
| Voidage / %              | <1.0 | 3.4   | 2.8  |                   |
| Marshall stability / 60°C, kN | 7.9  | 8.5   | 68.6 | JTG E20-2011 T0709 |
| Dynamic stability / 60°C, time/mm | 815  | 4875  | 10280| JTG F20-2011 T0715 |
| Biggest flexural-tensile strain / -10°C, × 10^6 | 3765 | 4426  | 5024 | JTG F20-2011 T0719 |

3.2. Results of composite material fatigue experiment
In accordance with the requirements of steel deck composite beam experiment, steel plate thickness should be 12 mm and asphalt pavement thickness should be 70 mm. Stress pattern is used for control. According to the load and deflection relation curve, Stress level of structure made of three typical pavement materials with a 0.6mm deflection is used as controlling load. Please refer to table 3.

Measured temperature is 25°C, loading waveform is half Sine wave and load frequency is 10 Hz. GA10 flexural modulus is 500 MPa with a 0.25 poisson's ratio; SMA10 flexural modulus is 400 MPa with a 0.25 poisson's ratio; EA10 flexural modulus is 600 MPa with a 0.25 poisson's ratio; steel plate flexural modulus is 210000 MPa with a 0.30 poisson's ratio (2012 Wan, Wang and Wang).

| Kind of asphalt mixture | GA10 | SMA10 | EA10 |
|-------------------------|------|-------|------|
| Deflection 0.6mm corresponding load/KN | 6.45 | 5.10  | 9.90  |

By adopting determined composite beam fatigue experiment method, we have done a GA10, SMA10, EA10 composite beam fatigue experiment. When the steel deck asphalt pavement cracks, delaminates or has a sudden testing curve displacement, experiments will be terminated. Elastomer modified asphalt SMA10 fatigue test curve is shown in figure 4.

![Figure 4. Steel deck SMA 10 composite beam fatigue experiment curve.](image)

With composite beam fatigue experiment raw data, damage variable D of three kinds of pavement materials is calculated and its relationship with times of acting is established, as shown in figure 5, 6 and 7.
Figure 5. GA10 composite beam damage variable D and times of fatigue fitting curve.

Figure 6. SMA10 composite beam damage variable D and times of fatigue fitting curve.

Figure 7. EA10 composite beam damage variable D and times of fatigue fitting curve.

With logarithmic function, we did data fitting between fatigue damage variable of three materials and times of fatigue, and established fatigue damage equation for three kinds of asphalt mixture.

Gussasphalt GA10: \( D = 0.0231 \ln(n) - 0.0505 \) (\( R^2 = 0.9394 \)) (5)

Modified asphalt SMA10: \( D = 0.0452 \ln(n) - 0.2088 \) (\( R^2 = 0.9348 \)) (6)

Epoxy asphalt mixture EA10: \( D = 0.0422 \ln(n) - 0.2460 \) (\( R^2 = 0.9427 \)) (7)

It can be found from figure 5-7: (1) Composite model fatigue damage rate coefficient obtained by fitting can reflect fatigue damage rate of different materials. The faster fatigue damage is, the faster its internal parts decay and the shorter its fatigue life is, so this coefficient can not only reflect the material fatigue process change rule, but also predict fatigue life length. (2) Except material elastic
modulus, fatigue damage rate of composite beam made of three typical pavement materials is also related to mixture composition. Epoxy asphalt mixture modulus is the highest and corresponding fatigue damage rate is the fastest; gussasphalt modulus follows, but fatigue damage rate becomes the slowest; modified asphalt SMA elastic modulus is the smallest, but its fatigue damage rate is the fastest because it has limited anti-cracking ability due to its embedded crowded structure. (3) Gussasphalt mixture contains much asphalt (Chen, 2011), compact structure and only a few microdefects, so it has excellent fatigue durability and smallest composite beam fatigue damage rate (Sun, 2005).

4. Conclusions
Through analysing the steel deck pavement composite beam test model, fatigue damage model and fatigue damage of three materials, we have the following main conclusions.

(1) By comparing and analysing measured results of composite beam model and finite analysis results as well as real bridge finite analysis results, we find that test model can well reflect deformation characteristics of orthotropic steel deck, which can be applied in steel bridge deck asphalt pavement fatigue tests.

(2) Steel deck pavement composite beam fatigue damage model, which is based on damage mechanics and analytic method, can be used for calculating composite beam fatigue test damage variables and analysing damage rules.

(3) Through analysing composite beam test and fatigue damage rule of the three typical pavement materials, GA10, SMA10 and EA10, we put up with fatigue damage formulas for the three pavement structures:
\[ D = 0.0452 \ln(n) - 0.2088 \]
\[ D = 0.0231 \ln(n) - 0.0505 \]
\[ D = 0.0422 \ln(n) - 0.246 \]
and we find that the two are closely related.

(4) By using logarithmic coefficients to reflect fatigue damage rate, we find that stiffening pavement system has the smallest fatigue damage rate and modified asphalt SMA has the biggest damage rate. That is to say, under the same use condition, gussasphalt pavement has a longer service life. This finding can better guide steel deck pavement structure design.

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