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Dynamic analysis of pavement on long span steel bridge decks

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Abstract: In order to analyze the dynamic response of pavement on long-span steel bridge decks under random dynamic loads, the irregularities of the pavement surface is simulated with the power spectrum density function, and the random load is calculated according to a vehicle vibration equation of vehicle model. The mechanical responses of three different cases are compared by using a transient dynamic analysis method, i. e., under random dynamic load, constant moving load and dead load respectively. The results indicate that the mid-span of two adjacent transversal diaphragms is the worst load position. The maximum vertical displacement and the maximum transversal tensile stress of the pavement are 1.33 times and 1.39 times as much as those when only considering the impact coefficients. This study not only provides a theoretical basis for the mixture design and structural design of pavement, but also puts forward higher demand on the construction and maintenance for steel deck pavement.

Key words: steel deck pavement; finite element method; dynamic analysis; impact coefficient

The pavement on long span steel bridge decks is subjected to the heavy impact of loaded truck wheels imposed by the passage of millions of trucks during several decades of its service life, and the diseases of bridge deck pavement are mainly caused by traffic. The additional dynamic load is generated in the interaction between wheels and the pavement with roughness[1]. Therefore, it does not guarantee precision if one analyzes the mechanical characteristics of steel deck pavement by using the static analysis method.

Most overseas theories of steel deck pavement systems focus on the static analysis of orthotropic deck system under vehicle loads[2-4]. Domestic scholars have also made systematical research on the static analysis of bridge deck pavement systems[5-6]. A vehicle load was defined as a moving constant load along the longitude of pavement surface in the general literature[7]. Then the mechanical characteristics of the deck pavement system were analyzed under the uniform moving load. In the present studies, only the impact coefficients were considered in the simulation of vehicle load. The results of the composite beam fatigue test on the steel bridge deck epoxy asphalt concrete surfacing shows that the fatigue life of steel deck pavements can meet the design demands based on the static equivalent principle[6].

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In this paper, the dynamic response of pavement with roughness is studied under random dynamic loads generated by vehicles. The mechanical characteristics of pavement under three different situations, i. e., under random dynamic load, under constant dynamic load and under dead load are compared. It can provide a theoretical basis for the selection of pavement material, lab tests and the construction and maintenance of pavement.

1 Dynamic Calculation Model

This paper is based on the orthotropic deck configuration of the Runyang Yangtze River Highway Bridge. Seven trapezoidal stiffeners in a transversal direction and three spans in a longitudinal direction of the bridge are chosen. Totally, there are four diaphragms. The distance between every two diaphragm plates is 3.75 m. The calculation parameters are shown in Tab. 1 and Tab. 2. The FE model of steel deck pavement system is shown in Fig. 1. BZZ-100 is taken as the load grade, and the standard tyre pressure is 0.707 MPa. The specific load diagram is shown in Fig. 2(a).

The calculation results show that the worst load case of maximum transversal tensile stress/strain is a symmetrical load on the longitudinal rib[6]. This load case is conducted in this paper, as is shown in Fig. 2(b).

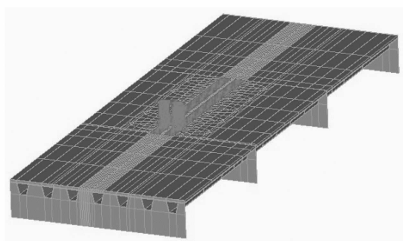

Fig. 1 Local finite element analysis model of bridge pavement

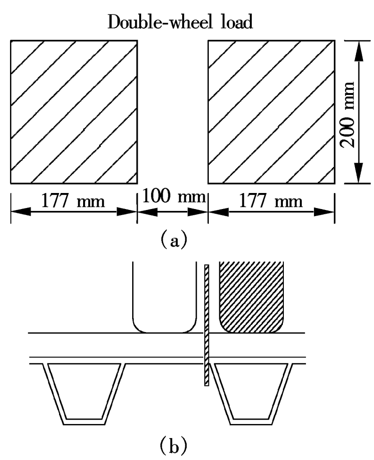

Fig. 2 Load condition. (a) Area of load; (b) Calculation position

Tab. 1 Geometric size of the dynamic calculation model mm

Thickness of bridge deck	Opening width of U-rib	Height of U-rib	Thickness of U-rib	Spacing of U-rib	Thickness of pavement
14	300	280	8	600	55

Tab. 2 Material parameters of the dynamic calculation model

Elastic modulus of steel plate/GPa	Poisson ratio of steel plate	Density of steel plate/($kg\cdot m^{-3}$)	Elastic modulus of asphalt pavement/MPa	Poisson ratio of pavement	Density of pavement/($kg\cdot m^{-3}$)
210	0.3	8.7×10^3	680[8]	0.25	2.6×10^3

2 Random Dynamic Load between Pavement Surface and Vehicle

2.1 Pavement surface roughness

The randomness of the pavement surface roughness can be represented by a periodic modulated random process. In ISO 8608 specifications, the road surface roughness, which is represented in a formula between the velocity power spectral density(PSD) and the displacement PSD, is related to the vehicle speed. The general form of the displacement PSD of the road surface roughness is given as[9-12]

$$S_d(f)=S_d(f_0)\left(\frac{f}{f_0}\right)^{-a} \tag{1}$$

where f_0(=0.1 cycle/m) is the reference spatial frequency, a is an exponent of the PSD, and f is the spatial frequency (cycle/m). Eq. (1) gives an estimate of the degree of roughness of the road from the value of $S_d(f_0)$. This surface roughness classification is based on a constant vehicle velocity PSD, where $a=2$. $S_d(f_0)$ is the coefficient of the irregularity of the pavement. The values of the coefficient are 5×10^6, 20×10^6, 80×10^6, 260×10^6, which correspond to four grades, that is, very good, good, ordinary and bad respectively.

The pavement surface roughness function $r(x)$ in the time domain can be simulated by applying the inverse fast Fourier transformation to $S_d(f_i)$, which is given as

$$r(x)=\sum_{i=1}^{N}\sqrt{4S_d(f_i)\Delta f}\cos(2\pi f_i x+\theta_i) \tag{2}$$

where $f_i=i\Delta f$ is the spatial frequency, $\Delta f=1/(Nl)$, l is the distance interval between successive ordinates of the surface profile, and N is the number of data points; θ_i is the set of independent random phase angles uniformly distributed between 0 and 2π.

The coefficient of the irregularity of the pavement is 20×10^6, owing to the good roughness of the asphalt concrete pavement for new bridges[13]. The curve of the irregularity of the pavement is shown in Fig. 3 (The abscissa refers to the distance along the longitudinal direction of the bridge).

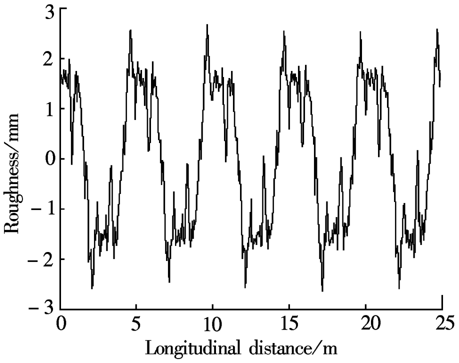

Fig. 3 Roughness of pavement surface

2.2 Vehicle model

A quarter-car model with two degrees of freedom[14] applied in this paper is shown in Fig. 4. m' denotes the mass of the car body and m denotes the mass of the tyre. k_t and k_s denote the suspension stiffness of the car body and the tyre stiffness. c_s and c_t denote the suspension damp and the tyre damp. The vertical displacement of m' and m are denoted as u' and u. The parameters of a standard vehicle are shown in Tab. 3.

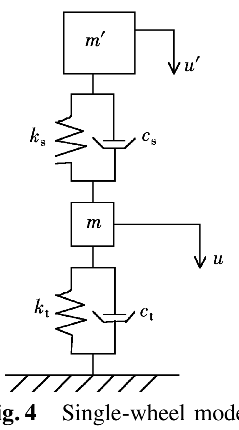

Fig. 4 Single-wheel model

Tab. 3 Parameters of standard vehicle

Load grade	m'/kg	m/kg	k_t/($kN\cdot m^{-1}$)	k_s/($kN\cdot m^{-1}$)	c_s/($kN\cdot s\cdot m^{-1}$)	c_t/($N\cdot s\cdot m^{-1}$)
BZZ-100	9 000	1 000	1 900	480	3	14

2.3 Random dynamic load

The unknown displacement vector of the vehicle is $\boldsymbol{U}(u', u)$. The random dynamic load was calculated by using the following equation:

$$\boldsymbol{M}\ddot{\boldsymbol{U}}+\boldsymbol{C}\dot{\boldsymbol{U}}+\boldsymbol{K}\boldsymbol{U}=\overline{\boldsymbol{F}} \tag{3}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ represent the mass, the damping and the stiffness, respectively; and $\overline{\boldsymbol{F}}$ represents the vehicle load acting on the bridge deck.

The matrix $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ can be given as

$$\boldsymbol{M}=\begin{bmatrix} m & 0 \\ 0 & m' \end{bmatrix},\ \boldsymbol{C}=\begin{bmatrix} c_t+c_s & -c_s \\ -c_s & c_s \end{bmatrix},\ \boldsymbol{K}=\begin{bmatrix} k_t+k_s & -k_s \\ -k_s & k_s \end{bmatrix} \tag{4}$$

The interaction between tyre and bridge can be calculated by the following equation:

$$\boldsymbol{F}=k_i\Delta_i+c_i\dot{\Delta}_i \tag{5}$$

where k_i is the stiffness of the i-th tyre, and c_i is the damping coefficient of the i-th tyre. The vertical displacement between the i-th tyre and the bridge can be given as

$$\Delta_i=u_i-(-r_i) \tag{6}$$

where u_i is the vertical displacement from the static balance position of the i-th tyre, and r_i represents the roughness of the pavement surface.

Provided the area of the load is constant, the value of the uniform load is variable when the truck moves on the pavement surface. In the following figures, the abscissa refers to the distance from one end of the mid span to the loading point. The dynamic load curve is shown in Fig. 5. The peak of the dynamic load appears in the mid-span of two adjacent diaphragms.

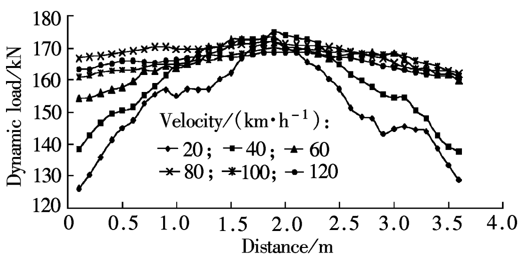

Fig. 5 Discrete random variables of dynamic load

From Fig. 5, when the velocities vary from 20 to 40 km/h, the peak of the dynamic load increases. However, when the velocities vary from 40 to 120 km/h, the peak of the dynamic load decreases.

3 Dynamic Analysis of Steel Deck Pavement

3.1 Maximum vertical displacement

In Fig. 6, the peak value appears when the load moves towards the mid-span of two adjacent diaphragms. The minus indicates that the direction is vertically downwards. The change curves are smooth, and the peak value point appears around the mid-span.

When the velocities vary from 20 to 40 km/h, the peak value of the maximum vertical displacement increases a little. When the velocities vary from 40 to 120 km/h, the peak value of maximum vertical displacement decreases.

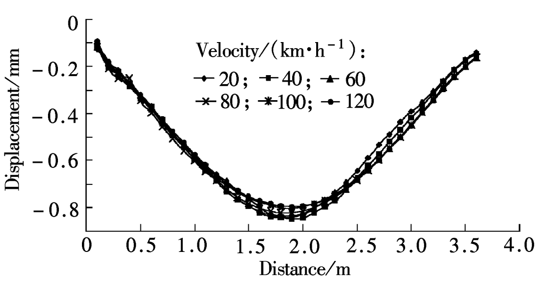

Fig. 6 Maximum vertical displacement

3.2 Maximum transversal tensile stress

In Fig. 7, when the load moves to the mid-span of two adjacent transversal diaphragms, the peak value of maximum transversal tensile stress appears, the node of which appears around the middle of two adjacent transversal diaphragms. As the pavement function is random, the dynamic load is random. When the dynamic load moves along in a longitudinal direction, the maximum transversal tensile stress takes on a curve with strong fluctuations.

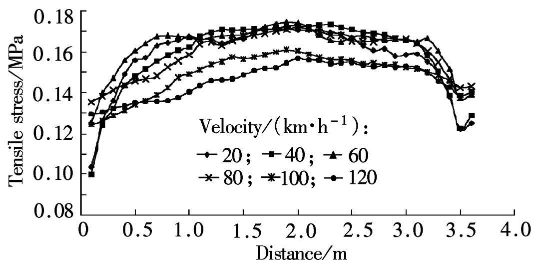

Fig. 7 Maximum transversal tensile stress

When the velocities vary from 20 to 60 km/h, the peak value of maximum transversal tensile stress increases a little; when the velocities vary from 60 to 120 km/h, the peak value of maximum transversal tensile stress tends to decrease. The difference between the maximum 0.174 MPa and the minimum 0.156 MPa is 0.018 MPa, which almost accounts for 10% of the maximum 0.174 MPa. The peak value of maximum transversal tensile stress of the whole deck pavement appears when the load moves around the middle of two adjacent transversal diaphragms. Therefore, the velocities, to some extent, influence the maximum transversal tensile stress.

3.3 Comparison of the calculation results under different load cases

We adopt the same calculation model and parameters to obtain the peak values of dynamic response which is under the moving constant load and the static load. When calculating the vehicle load, the impact coefficient is considered only and the results of the three different load cases are indicated in Tab. 4. (The correspondent velocities in terms of moving constant load and the moving random load are 60 km/h).

Tab. 4 Response of pavement under different load cases

Load form	Peak value of maximum vertical displacement/mm	Peak value of maximum transversal tensile stress/MPa
Static	0.624	0.132
Moving constant load	0.625	0.125
Random dynamic load	0.836	0.174

In Tab. 4, the impact coefficient and damping are taken into consideration without roughness; the peak value of maximum transversal tensile stress under the moving constant is smaller than the static calculation. However, the difference is little enough to be ignored. From the maximum vertical displacement point of view, when considering the roughness, the peak value is 0.836 mm; when considering the impact coefficient, the peak value is 0.625 mm; the former is 1. 33 times larger than that of the latter. From the maximum transversal tensile stress point of view, when considering the roughness, the peak value is 0. 174 MPa; when considering the impact coefficient, the peak value is 0. 125 MPa; the former is 1. 39 times larger than that of the latter.

4 Conclusions

The dynamic response on the orthotropic steel deck pavement is studied. The results show that only taking the impact coefficient into consideration is unreasonable in a dynamic analysis of a pavement system. Based on the discussion, the following can be concluded:

1) The mid-span between two adjacent transversal diaphragms is the worst load position under different velocities, and the maximum vertical displacement and the maximum transversal tensile stress reach the peak values.

2) The variation in velocities has some influence on the maximum vertical displacement and the maximum transversal tensile stress on the pavement.

3) The peak dynamic response increases to a large margin when considering the roughness of the pavement. Thus, it is suggested taking the dynamic coefficient as 1. 8 for the design and calculation of the deck pavement structure and the conduction of fatigue tests on the composite beam.

4) This study is supposed to provide the mechanical index in a stress-strain equivalent method in terms of fatigue tests on the composite beam, and it is expected to be applied to the study of materials and structures of pavement as theoretical references.

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大跨径钢桥面铺装动响应分析

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摘要:为了研究车辆随机荷载作用下的大跨径钢桥面铺装层动响应,首先根据目前钢桥面铺装的平整度现状,利用功率谱密度函数模拟桥面不平度;然后选取单轮车辆模型计算由桥面不平度引起的行驶车辆随机动荷载;最后采用瞬态动力分析方法计算了铺装层的竖向位移及最大横向拉应力等主要力学响应,并与以往的移动恒载作用下铺装层的动响应及静力计算结果做了比较.分析表明,针对铺装层而言,相邻的 2 块横隔板的跨中位置为最不利荷载位置;考虑桥面不平度情况下铺装层的最大竖向位移和最大横向拉应力的峰值分别是只考虑冲击系数的移动恒载作用下的 1. 33 倍和 1. 39 倍.研究结果为铺装层的混合料和结构设计提供了理论依据,对桥面施工及维护提出了严格要求.

关键词:钢桥面铺装;有限单元法;动力分析;冲击系数

中图分类号:U443. 33