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Axle-equivalent method of steel-deck pavement

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Abstract: An index system of steel deck pavement design is proposed according to the study and classification of failure types. Furthermore the axle-equivalent equation is presented according to the fatigue principle of pavement structures. Based on indoor experiments and theoretical analysis, this paper studies the stress characteristics of three different axle types which are corresponding with the other three typical pavement structures, and also presents the parameters of each axle's equivalent formula. The three axle types include single-axle single-wheel, single-axle double-wheel and double-axle double-wheel. According to analyses of influential factors such as climate, environment, traffic and stress condition, the developed axle equivalent formula and the parameters modified by the field test data can be applied in the design of a new bridge deck pavement and the assessment of an existing bridge deck pavement.

Key words: steel bridge; asphalt mixture; pavement; fatigue-equivalent principle; axle-equivalent method; index

Deck paving is a key technical issue in the construction of steel bridges. The conditions and requirements of surfacing on the steel deck are far more stringent than those on ordinary road pavements. As combined deformation of steel bridge and peculiarity of orthotropic steel-deck structure under vehicle-load, temperature, wind-load and earthquake, the structural behavior of steel-deck pavement is very complex, experience and theoretical research should be taken together.

1 Service Conditions of Steel-Deck Pavement

1.1 Weather and environmental condition

The weather conditions include sun radiation (sunlight and cloudage), air temperature, wind speed, rainfall, snowfall and humidity. Sun radiation can directly be denoted as an air temperature equivalent. Air temperature of the weather condition is the most influential factor on steel-deck pavement. According to the field data of steel-deck pavement of long-span steel-box bridges in China, as the maximum air temperature was 34 ℃, the temperatures of steel-deck and asphalt mixture pavement were 62 and 69.5 ℃, respectively. According to the data and the weather conditions of the steel-box bridges deck pavement of Jiangyin Yangtze River Bridge, Nanjing Second Yangtze River Bridge and Runyang Yangtze River Bridge, their design temperature ranges of steel-deck pavement were all −15 to +70 ℃[1,2], and the design temperature range of the steel-deck pavement of Xiamen Haicang Bridge was +5 to +70 ℃[3]. Furthermore, steel-deck pavement may be influenced by the other environmental conditions such as earthquakes and so on.

1.2 Traffic conditions

Different kinds of traffic and their distribution results in different kinds of damage or failure to steel-deck pavement, so the traffic conditions on steel-deck pavements should be investigated. Presently, the traffic across rivers is roughly computed by each vehicle-type ratio, rated load, over-loading vehicle ratio and over-loading proportion of different kinds of traffic and axle-load distributions. These are investigated and computed according to the highways or bridges built nearby. But in the steel-deck pavement of building or rebuilding bridges and rebuilding pavement structure design, it is more important to investigate and compute each vehicle-type, axle-type, wheel-type and different axle-load distribution ratio for any given traffic situation. And the axle-equivalent method of steel-deck pavement structure design should be investigated based on the fatigue-equivalent principle or rutting-equivalent principle.

1.3 Structural behavior of steel-deck pavement

In the steel-deck asphalt mixture pavement, the main failure types of pavement are related to the local structural behavior and deformation of steel-deck. So the local girder section of an orthotropic steel-deck pavement was modelled as a mechanical analysis object. The orthotropic steel-deck pavement was as-

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sumed as uniform, continuous and containing isotropy elastic materials. Taking the steel-box bridges deck structures of Jiangyin Yangtze River Bridge, Xiamen Haicang Bridge, Nanjing Second Yangtze River Bridge and Runyang Yangtze River Bridge as examples, the structural behaviors of steel-deck asphalt mixture pavement were analyzed. The computing model included four transverse slabs and ten longitudinal ribs[1-3].

Under single-axle double-wheel axle load, the FEM computing results of the maximum transverse tensile stress or strain of steel-deck pavement and the maximum shearing stress between pavement and steel-deck were regressed according to the power function $X = aP^b$. Where X is one of the maximum transverse tensile stress σ_x (MPa), the maximum transverse tensile strain ε_x ($\mu\varepsilon$) or the maximum shearing stress between pavement and steel deck τ_{xy} (MPa); P is axle load (kN). Their regress coefficients are listed in Tab. 1.

Tab. 1 Regress coefficients of FEM results

Names of bridges	$\sigma_x = a_1 P^{b_1}$			$\varepsilon_x = a_2 P^{b_2}$			$\tau_{xy} = a_3 P^{b_3}$		
	a_1	b_1	R^2	a_2	b_2	R^2	a_3	b_3	R^2
Jiangyin Yangtze River Bridge	0. 001 9	0. 983 9	0. 999 9	4. 368 9	0. 999 1	1. 000 0	0. 001 6	1. 000 8	0. 999 7
Xiamen Haicang Bridge	0. 002 3	0. 998 4	1. 000 0	3. 282 8	1. 000 5	0. 999 6	0. 002 0	1. 004 7	1. 000 0
Nanjing Second Yangtze River Bridge	0. 002 1	1. 004 7	1. 000 0	3. 646 5	1. 001 4	1. 000 0	0. 001 7	1. 013 9	0. 999 9
Runyang Yangtze River Bridge	0. 002 0	0. 999 9	1. 000 0	3. 312 9	1. 000 5	1. 000 0	0. 001 9	0. 999 3	1. 000 0

2 Design Index and Axle-Equivalent Principle

The final yearly accumulative total traffic of steel-deck pavement design can be computed according to the axle-equivalent method of different axle loads. The axle-equivalent method should agree with the same equivalent principle, namely steel-deck pavement structure under different axle loads results in the same damage or failure extent. In other words, the steel-deck pavement structure computed by axle-load equivalent was the same as the one computed by different axle loads according to its design index[4-6]. The axle-equivalent method of steel-deck pavement is proposed according to the two design indices mentioned. One axle-equivalent formula is proposed according to the maximum transverse tensile stress which can also be replaced by the maximum strain or the maximum shearing stress between pavement and steel-deck. The other axle-equivalent formula can be proposed according to the rutting index and should comply with the rutting-equivalent. The axle-equivalent method of steel-deck pavement has been investigated based on fatigue equivalent in this paper.

3 Axle-Equivalent Method of Steel-Deck Asphalt Mixture Pavement

3.1 Axle-equivalent method of steel-deck pavement based on fatigue rules

The axle-equivalent method of steel-deck asphalt mixture pavement was analyzed based on FEM as follows: the ratios of the maximum transverse tensile stresses or strains of steel-deck pavement or the maximum shearing stresses between pavement and steel-deck under single-axle double-wheel of different axle loads can be denoted as

$$\frac{\sigma_{x1}}{\sigma_{x2}} = \frac{a_1 P_1^{b_1}}{a_1 P_2^{b_1}} = \left(\frac{P_1}{P_2}\right)^{b_1} \tag{1a}$$

$$\frac{\varepsilon_{x1}}{\varepsilon_{x2}} = \frac{a_2 P_1^{b_2}}{a_2 P_2^{b_2}} = \left(\frac{P_1}{P_2}\right)^{b_2} \tag{1b}$$

$$\frac{\tau_{xy1}}{\tau_{xy2}} = \frac{a_3 P_1^{b_3}}{a_3 P_2^{b_3}} = \left(\frac{P_1}{P_2}\right)^{b_3} \tag{1c}$$

where P_1 is the standard axle load (kN), P_2 is the axle load for different types of exchanged vehicles (kN), and b_i ($i = 1, 2, 3$) are constants.

As the fatigue characteristic of asphalt mixture is taken into account, the allowable tensile stress σ_R, allowable strain ε_R or allowable shearing stress τ_R under different axle loads can be denoted as

$$\frac{\sigma_{R1}}{\sigma_{R2}} = \frac{A_1 N_1^{-\frac{1}{c_1}}}{A_1' N_2^{-\frac{1}{c_1'}}} \tag{2a}$$

$$\frac{\varepsilon_{R1}}{\varepsilon_{R2}} = \frac{A_2 N_1^{-\frac{1}{c_2}}}{A_2' N_2^{-\frac{1}{c_2'}}} \tag{2b}$$

$$\frac{\tau_{R1}}{\tau_{R2}} = \frac{A_3 N_1^{-\frac{1}{c_3}}}{A_3' N_2^{-\frac{1}{c_3'}}} \tag{2c}$$

where N_1 is equivalent action times of standard axle loads; N_2 is applied times of different axle loads for the exchanged vehicle type; A_i, c_i, A_i', c_i' ($i = 1, 2, 3$) are material constants.

Since the axle-equivalent object is the same steel-deck pavement structure, there are $A_1 = A_1'$, $c_1 = c_1'$ or $A_2 = A_2'$, $c_2 = c_2'$ and $A_3 = A_3'$, $c_3 = c_3'$, and then Eq. (2) can be simplified as

$$\frac{\sigma_{R1}}{\sigma_{R2}} = \left(\frac{N_1}{N_2}\right)^{-\frac{1}{c_1}} \tag{3a}$$

$$\frac{\varepsilon_{R1}}{\varepsilon_{R2}} = \left(\frac{N_1}{N_2}\right)^{-\frac{1}{c_2}} \tag{3b}$$

$$\frac{\tau_{R1}}{\tau_{R2}}=\left(\frac{N_1}{N_2}\right)^{-\frac{1}{c_3}} \tag{3c}$$

According to the axle-equivalent fatigue-equivalent principle of steel-deck pavement, Eq. (3) can be deduced as

$$\frac{\sigma_{R1}}{\sigma_{R2}}=\frac{\sigma_{x1}}{\sigma_{x2}} \tag{4a}$$

$$\frac{\varepsilon_{R1}}{\varepsilon_{R2}}=\frac{\varepsilon_{x1}}{\varepsilon_{x2}} \tag{4b}$$

$$\frac{\tau_{R1}}{\tau_{R2}}=\frac{\tau_{xy1}}{\tau_{xy2}} \tag{4c}$$

Substituting Eqs. (1) and (3) into Eq. (4) it will produce

$$\frac{N_1}{N_2}=\left(\left(\frac{P_1}{P_2}\right)^{b_i}\right)^{-c_i}=\left(\frac{P_2}{P_1}\right)^{b_ic_i}=\left(\frac{P_2}{P_1}\right)^{n_i} \qquad n_i=b_ic_i \tag{5}$$

Eq. (5) is the axle-equivalent formula proposed according to the maximum transverse tensile stress, strain of steel-deck pavement or the maximum shearing stress between pavement and steel-deck, but the exponents of different design indices are different.

3.2 Calculation of parameter *b*

In order to analyze changing law of parameter b of simplified ratio formula (1) of each design index for single-axle double-wheel axle load, according to FEM computing results of steel-deck pavement for Jiangyin Yangtze River Bridge, Xiamen Haicang Bridge, Nanjing Second Yangtze River Bridge and Runyang Yangtze River Bridge, the parameters b and their averages $\bar{b}$ of the maximum transverse tensile stresses or strains of steel-deck pavement, the maximum shearing stresses between pavement and steel-deck were regressed and listed in Tab. 2. The parameter averages $\bar{b}$ are all close to 1.

Tab. 2 Exponents of each index ratio formula

Design index	Jiangyin Yangtze River Bridge	Xiamen Haicang Bridge	Nanjing Second Yangtze River Bridge	Runyang Yangtze River Bridge	Average $\bar{b}$
σ_x	0.983 9	0.998 4	1.004 7	0.999 9	0.998 2
ε_x	0.999 1	1.000 5	1.001 4	1.000 5	1.000 6
τ_{xy}	1.000 8	1.004 7	1.013 9	0.999 3	1.004 7

3.3 Fatigue tests and calculation of parameter *c*

Presently, the fatigue characteristics of steel-deck pavement are investigated mainly by indoor tests, not by fatigue tests of more expensive test bridges which have more reasonable test conditions. In order to obtain indoor fatigue test results fatigue tests of composite-beams made of steel bridge deck and asphalt mixture pavement are more reasonable test methods. Within a limited test, the practical service condition of asphalt mixture for steel-deck pavement can be better reflected by an indirect tensile splitting fatigue test or a small-beam bending fatigue test that can reflect the fatigue characteristics of the asphalt mixture.

As for steel-deck guss asphalt concrete pavement such as that is found on Jiangyin Yangtze River Bridge and others, while falling short of the fatigue test results of composite-beam for steel-deck pavement, the fatigue characteristic of steel-deck guss asphalt concrete pavement was expressed by indirect tensile splitting fatigue tests. The fatigue test results are regressed according to Eq. (2a), and the regress coefficients of fatigue equations proposed are listed in Tab. 3.

Tab. 3 Fatigue equations of steel deck guss asphalt pavement

$N=A_1\sigma^{-c_1}$			$N=A_1'(\sigma/S)^{-c_1'}$		
A_1	c_1	R^2	A_1'	c_1'	R^2
22.721	4.347 8	0.993 5	0.032 8	4.347 8	0.993 5

As for steel-deck modified asphalt SMA pavement such as that is found on Xiamen Haicang Bridge and others, also falling short of the fatigue test results of composite-beam for steel-deck pavement, the fatigue characteristic of steel-deck modified asphalt SMA pavement was expressed by the small-beam bending fatigue tests. Its fatigue test results and bearing stress and strain of pavement computed by the exchanging-section method of combining beam were regressed according to Eq. (2a), and the regress coefficients of fatigue equations proposed are listed in Tab. 4.

Tab. 4 Fatigue equations of SMA pavement

$N=A_1\sigma^{-c_1}$			$N=A_2\varepsilon^{-c_2}$		
A_1	c_1	R^2	A_2	c_2	R^2
15 473	5.319 8	0.933 5	6.0×10^{18}	5.305 8	0.944 9

As for steel-deck epoxy asphalt concrete pavement such as that is found on Nanjing Second Yangtze River Bridge and others, the fatigue tests of composite-beams for steel-deck pavement and FEM computing results were regressed according to Eq. (2a), and the regress coefficients of fatigue equations proposed are listed in Tab. 5.

The irrecoverable strength loss accumulation under repeated axle loads results in fatigue crack of asphalt mixture. There is almost no difference in the fatigue characteristics of steel-deck asphalt mixture pavement with the same properties and parameters. So the fatigue equations proposed in Tabs. 3, 4 and 5 can be applied to steel-deck materials pavement made of these same or similar asphalt mixtures.

Tab. 5 Fatigue equations of epoxy asphalt pavement

$N = A_1 \sigma^{-c_1}$			$N = A_2 \varepsilon^{-c_2}$			$N = A_3 \tau_{xy}^{-c_3}$		
A_1	c_1	R^2	A_2	c_2	R^2	A_3	c_3	R^2
8 176. 3	6. 252 3	0. 987 0	9.934×10^{23}	6. 252 5	1. 000	0. 978 8	6. 251 8	0. 999 0

As for other asphalt mixture steel-deck pavement such as guss asphalt concrete base course + dense-graded asphalt concrete pavement, modified asphalt SMA base course + dense-graded asphalt concrete pavement, guss asphalt concrete base course + modified asphalt SMA pavement, guss asphalt concrete base course + epoxy asphalt concrete pavement of Nancha Bridge of Runyang Yangtze River Bridge and others[2], their fatigue characteristics should be investigated by fatigue tests and mechanical analysis of composite-beams to arrive at their fatigue equations. Subsequently, the fatigue equations proposed will be applied to calculate parameter n in the axle-equivalent formula of steel-deck pavement based on fatigue equivalent.

3. 4 Parameter *n* in single-axle double-wheel axle loads equivalent formula

As for steel-deck guss asphalt concrete, modified asphalt SMA and epoxy asphalt concrete pavement, their exponent averages $\bar{b}_i$ (see Tab. 2) and their corresponding parameters c_i (see Tabs. 3, 4 and 5) of fatigue equations were substituted into Eq. (5). The axle-equivalent parameters n_i are listed in Tab. 6. According to Tab. 6, there is almost no difference in their axle-equivalent parameters n_i of the maximum transverse tensile stresses, strains of steel-deck pavement or the maximum shearing stress between pavement and steel-deck. So their averages $\bar{n}$ of each design index under single-axle double-wheel different axle loads are also listed here.

Tab. 6 Equivalent exponents of each index

Steel-deck pavement materials projects	σ_x	ε_x	τ_{xy}	Average $\bar{n}$
Guss asphalt concrete	4. 340			4. 34
Modified asphalt SMA	5. 310	5. 309		5. 31
Epoxy asphalt concrete	6. 241	6. 256	6. 281	6. 25

3. 5 Axle-equivalent method of other axle-type and wheel-type axle loads

The basic axle-equivalent formula mentioned was based on all the single-axle double-wheel different axle loads for the exchanged vehicle type and standard axle load. In order to make the axle-equivalent formula of each design index uniform, other axle-type and wheel-type axle loads were all exchanged for single-axle double-wheel axle loads according to Eq. (5) which can be deduced as

$$\frac{N_1}{N_2} = \left(\left(\frac{1}{\alpha_i} \right) \left(\frac{P_1}{P_2} \right)^{b_i} \right)^{-c_i} = \alpha_i^{c_i} \left(\frac{P_2}{P_1} \right)^{n_i} \tag{6}$$

where α_i are ratios of the maximum transverse tensile stress of steel-deck pavement or the maximum shearing stress between pavement and steel-deck under the other axle-type and wheel-type axle loads to that under single-axle double-wheel axle loads.

As examples of single-axle single-wheel and double-axle double-wheel axle loads, according to FEM computing results of steel-deck pavement for Jiangyin Yangtze River Bridge[6], Xiamen Haicang Bridge, Nanjing Second Yangtze River Bridge and Runyang Yangtze River Bridge, the ratios α_i of the maximum transverse tensile stresses or strains of steel-deck pavement or the maximum shearing stresses between pavement and steel-deck are computed and listed in Tab. 7. According to Tab. 7, whether single-axle single-wheel or double-axle double-wheel axle load, there is almost no difference in ratios α_i and the averages $\bar{\alpha}_i$ in three cases: the maximum transverse tensile stresses, strains of steel-deck pavement or the maximum shearing stresses between pavement and steel-deck.

So by associating Eq. (5) with Eq. (6), the axle-equivalent formula proposed of steel-deck pavement based on fatigue equivalent is

$$N_1 = C \left(\frac{P_2}{P_1} \right)^n N_2 \tag{7}$$

where n is the exponent of axle loads for the exchanged vehicle of axle equivalent. According to Tab. 6, the

Tab. 7 Different ratios of each index

Names of bridges	Index σ_x		Index ε_x		Index τ_{xy}	
	Single-axle single-wheel	Double-axle double-wheel	Single-axle single-wheel	Double-axle double-wheel	Single-axle single-wheel	Double-axle double-wheel
Jiangyin Yangtze River Bridge	2. 18	0. 58	2. 20	0. 57	2. 09	0. 48
Xiamen Haicang Bridge	2. 08	0. 57	2. 05	0. 58	2. 12	0. 52
Nanjing Second Yangtze River Bridge	2. 20	0. 65	2. 10	0. 63	2. 11	0. 50
Runyang Yangtze River Bridge	2. 14	0. 59	2. 12	0. 60	2. 12	0. 50
Average $\bar{\alpha}_i$	2. 15	0. 60	2. 12	0. 59	2. 11	0. 50

parameter n of its axle-equivalent formula proposed is 4. 34 for steel-deck guss asphalt concrete pavement, and the parameter n is 5. 31 for steel-deck modified asphalt SMA pavement, and the parameter n is 6. 25 for steel-deck epoxy asphalt concrete pavement. C is axle-type and wheel-type coefficient. It can be obtained by using Tab. 7 and Eq. (7). For example, the axle-type and wheel-type coefficient of single-axle single-wheel is $C = \bar{\alpha}^c = 165.6$, and the coefficient of single-axle double-wheel is $C = 1.0$, and the coefficient of double-axle double-wheel is $C = \bar{\alpha}^c = 0.02$ for the steel-deck guss asphalt pavement.

4 Conclusion

The axle-equivalent method and Eq. (7) of steel-deck pavement are proposed based on fatigue equivalent. The parameters a, b, c, n, α can be obtained by using this method after the FEA calculation and fatigue test data regress. Results also show that whether single-axle single-wheel or double-axle double-wheel axle load, there is almost no difference in each axle-equivalent parameter in three cases: the maximum transverse tensile stresses, strains of steel-deck pavement or the maximum shearing stresses between pavement and steel-deck. Furthermore, as for steel-deck each asphalt mixture pavement, the axle-equivalent formula proposed can be applied to steel-deck pavement made of these same or similar asphalt mixtures. But the formula should be modified according to field data.

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钢桥面铺装体系等效轴载换算方法

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摘要:通过对钢桥面铺装主要病害的研究与分类,提出了桥面铺装结构设计的指标参数体系,并应用疲劳等效的原理,推导了轴载等效换算公式.根据室内试验和理论分析,分别研究了3种典型的铺装结构对应3种不同轴载类型的受力特性,并提出了各自轴载换算公式的参数的取值.3种轴载类型包括:单轴单轮组、单轴双轮组、双轴双轮组.通过对桥面铺装的影响因素包括气候与环境、交通、受力状态等使用条件的分析,提出的轴载等效换算公式与参数取值经过现场测试数据进行修正后,可以应用于新建桥梁桥面铺装的设计和已建桥梁桥面铺装使用状况的评价.

关键词:钢桥;沥青混合料;铺装;等效疲劳原则;轴载换算;指标

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