Analysis of the influence of Chinese and foreign standard vehicle loads on the fatigue effect of orthotropic steel bridge decks

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Abstract. In view of the influence of Chinese and foreign standard vehicle loads on the fatigue effect of orthotropic steel bridge decks, the Chinese steel bridge specification JTG D64-2015 fatigue vehicle model III is selected and compared with Eurocode, BS5400 and AASHTO vehicle models. Ansys was used to establish a refined finite element model. Based on the analysis of fatigue stress influence surface, the effects of wheel load distribution, pavement diffusion, fatigue vehicle type and wheel track on fatigue effect were analysed, and the sensitivity of fatigue effect on different vehicle load parameters was discussed. The results show that the aspect ratio of wheel load has a significant influence on the fatigue stress influence surface. Besides, JTG D64 should introduce the wheel load distribution regulations according to the classification of vehicle. The pavement diffusion effect reference BS5400 adopts the 26.5° angular diffusion model. It was found that the orthotropic steel bridge deck designed according to AASHTO can no longer meet the current load requirements in China. The results obtained by fatigue design and evaluation according to JTG D64 vehicle model III are more accurate. The lateral probability distribution of the vehicle in JTG D64 is suitable for anti-fatigue design. Moreover, in the fatigue evaluation, the influence of the wheel track distribution on the fatigue details around the load should not be neglected.

1. Introduction
Since 2000, China has designed and built more than 100 bridges with orthotropic steel bridge decks. With the increasing traffic volume, the fatigue problem of steel bridges in China has become more and more prominent. In the inspection and maintenance, it is found that there are different degrees of fatigue cracking, which seriously affects the structural performance and operational safety. China does not officially introduce regulations for the anti-fatigue design and its inspection until the government issue the Specification for Design of Highway Steel Bridges (JTG D64-2015) (hereinafter we call it Specification of Steel Bridge) in 2015 and, the construction of bridges built before referring to the European specification Eurocode, the British specification BS5400 and the American specification
AASHTO LRFD. Therefore, the difference in load between Chinese and foreign vehicles is one of the reasons for the fatigue problem of steel bridges in China.

In response to this problem, many scholars have carried out in-depth analyses concerning the insufficiency of the combination of steel bridges and load status in China: Ruan Xin et al. [1] compared the WIM data of the Chinese highways and French highways, and they pointed out that although the traffic load changes are basically the same, the traffic volume and the values of vehicle parameters have huge difference. For the Specification of Steel Bridge, the assumption of vehicle load regulation in China remains to be discussed. Zhu Zhiwen et al. [2] analysed the fatigue vehicle model of freight-heavy highways and concluded that the fatigue research and evaluation based on AASHTO are of little applicability to the actual situation in China. Zhai Musai et al. [3, 4] conducted a full-scale fatigue test under the premise of discussing the vehicle load of different highways, and proposed the fatigue load model for different grades of highways, considered the fatigue factors such as bridge deck pavement as well. Zhang Qinghua et al. [5] conducted a full-scale fatigue test by simulating the vehicle walking effect. They stated that the fatigue characteristics of each key fatigue details are significantly different, and the hot spot stress method is recommended for fatigue evaluation.

Many researchers all over the world [1-7] point out that the fatigue effect of orthotropic steel bridge deck is significantly affected by local effects. Therefore, in this paper, Nanjing Yangtze River Third Bridge was selected as the study project, and China's current specification JTG D64-2015 is regarded as the research and evaluation basis. Using the stress-affected surface model, a comparative analysis was conducted, so as to investigate the fatigue effect affected by the difference of regulations concerning Eurocode and AASHTO LRFD. The analysis provides a reference for the improvement and revision of China's Specification of Steel Bridge.

2. FE model and stress influence surface
The construction of Nanjing Yangtze River Third Bridge adopts orthotropic streamlined flat steel beams with a height of 3.2 meters and a width of 37.5 meters (including wind nozzles). The standard section of steel box beams is 15 meters long, and there are four floorbeams with a spacing of 3.75 meters and the thickness of 12 mm. The thickness of steel box girder of emergency stop belt and heavy road deck is 16 mm. The deck longitudinal ribs are U-shaped longitudinal ribs, with the size of 300 mm × 280 mm × 8 mm, and the spacing of 600 mm. With Ansys unit SHELL181, an orthotropic bridge deck segment model was built, whose main beam material is Q345 steel FE model section is 15m in length (including 5 floorbeams with the height of 1m). In the transverse direction, there are 10 longitudinal ribs with the spacing of 6m, as shown in Figure 1. The model constrains the translational movement and torsion movement of the deck. The bottom of the transverse partitions at both ends are fixed-constrained simulated anchor-locking zones, and the lower edges of the three horizontal floorbeams are hinged.

![Figure 1 FE model of orthorhombic steel bridge deck (mm).](image-url)
Based on China's Specification of Steel Bridge, the fatigue load vehicle III was selected as the loading model, loaded by a single-axis wheel with the wheel load of 60kN. The landing length is 600mm and the landing width is 200mm. Evaluating the hot spot stress of rib to deck welds as fatigue detail A, and the rib to floorbeam welds as fatigue detail B, two typical fatigue detail analyses were conducted and the fatigue stress influence surface is shown in Figure 2. The characteristic values of stress influence surface are listed in Table 1.

According to Figure 2, the fatigue detail of the deck is short along the longitudinal sensitive area, and a large stress amplitude is generated when a single wheel passes; the fatigue detail of the floorbeam is significantly longer than that of the deck along the longitudinal sensitive area, but the stress amplitude caused by the passage of a wheel is relatively small. There is a significant difference between the influence of the fatigue detail of the deck and that of the floorbeam fatigue details. When studying the fatigue effect, the variation of the characteristic value of the influence surface under different load conditions should be considered. The depth research and evaluation should be carried out on this basis.

Table 1 Characteristic Values of Stress Influence Surface.

| Fatigue details | Transverse sensitive area (mm) | Longitudinal sensitive area (mm) | Most unfavorable lateral position (mm) | Maximum equivalent stress amplitude (MPa) |
|-----------------|--------------------------------|----------------------------------|---------------------------------------|----------------------------------------|
| A               | [-325,375]                     | [-300,600]                       | +300                                  | 93.83                                  |
| B               | [-3700,3700]                   | [-550,650]                       | +200                                  | 33.13                                  |

3. Effect of local action of wheel load

3.1 Influence of wheel load distribution

The difference in the area of wheel load will directly affect the calculation results of the fatigue effect. Due to the huge differences in vehicle types and load sizes in different countries, the distribution of wheel load is directly affected. Figure 3 shows the wheel load distribution of the vehicle load model based on standard fatigue models in China, Europe, and the United States. The three-wheel load aspect ratios are 1:3, 1:2, and 1:1. In order to simplify the analysis, three kinds of wheel pressures are 0.50 MPa, 0.46 MPa and 0.38 MPa under the load condition of 60 kN with each wheel.
From the characteristic values of stress influence surface under the loading for three kinds of wheels shown in Table 2, it is known that different distributions of the wheel have an obvious effect on the maximum stress amplitude of each detailed part. Compared with Specification of Steel Bridge, the result calculated according to AASHTO demonstrates that the detailed stress amplitude of the deck welds is decreased by 2.6% and the detailed stress amplitudes of floorbeam is decreased by 17.6% while the result calculated according to Eurocode shows that the detailed stress amplitude of deck is decreased by 12.6% and the detailed stress amplitude of floorbeam is decreased by 36.0%.

As found in the analysing results, there exists an apparent influence that the aspect ratio change of the wheel directly cause the change of characteristic values of stress influence surface, that is to say, the longitudinal and horizontal influence areas of the wheel are influenced by the wheel loading distribution. The sensitive detailed areas of the rib to deck welds are positively correlated with the longitudinal and horizontal sizes of the wheel while the detailed influence areas of rib to floorbeam welds are affected slightly by the loading size of the wheel. The differences, which uses different wheel loading distributions to assess the fatigue effect of orthotropic steel bridge deck, should not be neglected. Therefore, it is suggested that it is necessary to make a classification definition of wheel type and size when adapting the fatigue assessments of the wheel loading distribution model, whose results should base on the researches of China or some local areas. Eurocode provide a reference for China, whose fatigue load model IV specifies three kinds of wheel loading distribution models in accordance with different wheel models.

3.2 Influence of diffusion angle of pavement

Some researchers think that the stiffness and thickness of pavement have obviously affected the fatigue stress of each detailed part. Considering that the pavement of steel bridge and steel has considerable differences in the aspect of elastic modular, which could be neglected, and the diffusion effect of wheel load due to the bridge paving could be simplified with a specific diffusion angle. Because China's Specification of Steel Bridge lacks of the relative ordinances of diffusion angle of pavement, researchers from China always consult the angle of pavement with 45°, which is from the specification of concrete bridge. However, BS5400 suggests that the 1:2 radio (around 26.5°) diffusion angle should be adapted in the steel bridge pavement which commonly uses epoxy asphalt concrete.
The diffusion effect has a direct effect with elastic modulus of pavement and the elastic modular of the epoxy asphalt concrete is changeable due to the temperature, thus it is necessary to take the stress amplitude of fatigue details influenced by different diffusion angle of pavement into account.

To study the influence of the detail fatigue’ stress amplitude of orthotropic steel bridge deck due to different diffusion angles, the pavement of epoxy asphalt concrete with 50mm in thickness and the loading of wheel in JTG D64 fatigue model III are used for analysing the sensibility.

From Table 3, it is found that the stress amplitude of each detail is in decline as diffusion angle increase and the fatigue details of deck is the most sensitive. Compared the 45° diffusion model and the 26.5° diffusion model with bare plate model, the largest equivalent stress is decreased by 30.74% and 17.02%, which mentions that there exists an oblivious effect on the result due to different diffusion angles. When analysing steel bridge fatigue, it is advised that epoxy asphalt concrete with a 26.5° diffusion angle referred to BS5400 should be adapted to analysis and calculation because the fatigue analysis results are more dangerous which use 45° diffusion angle. The analysing result shows that the largest equivalent stress of bare plate model not considering pavement tends to be higher. That means that the fatigue loading has a safety redundancy due to considering the diffusion effect of pavement.

### Table 3 Influence of fatigue detail fatigue due to different radial angle.

| Fatigue details | Radial angle of the wheel | Longitudinal influent area (mm) | Horizontal influent area (mm) | Most unfavorable location in horizon (mm) | Largest equivalent stress (MPa) |
|-----------------|---------------------------|---------------------------------|-------------------------------|------------------------------------------|-------------------------------|
|                 | 0°                        | [-350,350]                      | [-300,600]                    | +300                                     | 93.83                         |
| A               | 26.5°                     | [-350,350]                      | [-300,600]                    | +300                                     | 77.86                         |
|                 | 45°                       | [-350,350]                      | [-300,600]                    | +300                                     | 64.99                         |
| B               | 0°                        | [-3700,3700]                    | [-550,650]                    | +200                                     | 33.72                         |
|                 | 26.5°                     | [-3700,3700]                    | [-550,650]                    | +200                                     | 32.24                         |
|                 | 45°                       | [-3700,3700]                    | [-550,650]                    | +200                                     | 30.29                         |

4. Effect due to fatigue vehicle model

#### 4.1 Influence of vehicle types

The fatigue detail of orthotropic steel bridge deck enjoys a shorter effect along its length and the stress amplitude when multi-axle truck gets through is in line with the carriage wheel. The influential area of floorbeam is longer than fatigue detail of deck along the length and it is also longer than the axle bases of connecting shaft. The stress superposition occurs during the loading process of multi-axle truck, which causes a larger stress amplitude but a decreased loading cycle number. Using standard vehicle models of other countries or single vehicle model to analyse fatigue would cause significant errors easily.

### Table 4 Equivalent axle loads and wheelbases of vehicles.

| Specifications and references | Type of vehicle | Axle weight of vehicle (kN) | Wheelbase (m) |
|------------------------------|-----------------|----------------------------|---------------|
| JTG D64                      | Four-axle       | 120 120 120 120            | 1.2 6.0 1.2   |
| AASHTO                       | Three-axle      | 24 108 108 - -              | 4.3 9.0       |
|                              | Two-axle        | 35 85 - - -                | 5.5           |
|                              | Three-axle      | 45 75 140 - -              | 3.0 5.0       |
|                              | Four-axle       | 40 80 125 125 -            | 3.0 6.5 1.5   |
|                              | Five-axle       | 40 70 100 100 110           | 3.5 5.0 4.0 1.5 |

China’s Specification of Steel Bridge adapts four-axle vehicle as standard by referring to Eurocode while AASHTO uses the variable spindle vehicle model. In order to study the feasibility of simplified
fatigue car model, the equivalent stress after the conversion to single vehicle passing is obtained via rain-flow counting and linear accumulated damage criterion, according to the type and load of vehicles in Nanjing Yangtze River Third Bridge, shown in Table 4.

The value of equivalent stress is calculated via equation (1):

\[ \Delta \sigma_{eq} = \left( \sum p \cdot \Delta \sigma^m \right)^{\frac{1}{n}} \]  

(1)

Where \( \Delta \sigma \) represents the equivalent stress caused by the passing of the single vehicle; \( p \) is the proportion of vehicles and \( \Delta \sigma_{eq} \) is the equivalent stress amplitude caused by vehicle passed once.

It can be seen from the calculation results in Table 5 that the design of fatigue vehicle model of Nanjing Yangtze River Third Bridge according to AASHTO cannot meet the current situation of vehicle load, and each of the fatigue detail is prone to cause cracking. The utilization of the vehicle model III of Specification of Steel Bridge can basically fit the current situation of vehicle load, but the fatigue evaluation results still have a deviation of 15%~20%. Therefore, for future design of orthotropic steel desk of bridges in China, the current China's Specification of Steel Bridge should be referenced as far as possible and the safety factor should be properly introduced. Moreover, it is not suitable to evaluate steel bridges only by single vehicle module according to the specifications, and it should be evaluated separately according to the actual traffic flow and different fatigue details.

Table 5 Stress amplitude of bicycle after conversion.

| Detail fatigue | Specifications and references | Equivalent stress(MPa) | Proportion of vehicles | Equivalent stress amplitude by single vehicle(MPa) |
|----------------|-------------------------------|------------------------|------------------------|-----------------------------------------------|
| A              | JTG D64                       | 111.09                 | -                      | 111.09                                        |
|                | AASHTO LRFD                   | 219.42                 | -                      | 107.99                                        |
|                | Reference [10]                | 69.00                  | 50%                    | 127.59                                        |
|                |                               | 116.95                 | 44%                    | 127.59                                        |
|                |                               | 127.50                 | 5%                     | 127.59                                        |
|                |                               | 120.01                 | 1%                     |                                                |
| B              | JTG D64                       | 69.83                  | -                      | 69.83                                         |
|                | AASHTO LRFD                   | 37.50                  | -                      | 37.50                                         |
|                | Reference [10]                | 24.12                  | 50%                    | 57.76                                         |
|                |                               | 40.06                  | 44%                    |                                                |
|                |                               | 65.46                  | 5%                     |                                                |
|                |                               | 55.54                  | 1%                     |                                                |

4.2 Influence of wheel track

The distribution of vehicles is random, so the lateral probability distribution of load should be considered in evaluation and analysis. The probability distribution of wheel transverse position proposed in the Specification of Steel Bridge is consistent with Eurocode, approximating to the normal distribution with standard deviation of 80mm. BS5400 adopts normal distribution model with standard deviation of 225mm to define transverse distribution of load. Many studies on wheel track distribution [11, 12] show that the standard deviation of vehicle lateral probability distribution is generally between 200 mm and 600 mm, and the wheel track probability distribution of vehicles in China is close to the normal distribution model with standard deviation of 400mm.

In order to study the fatigue effect of the transverse probability distribution of the wheel track on the typical fatigue details, it is considered that the wheel track satisfies the normal distribution. The most unfavourable loading position of the wheel is taken as an expected value according to the specifications, and standard deviation is used as the research parameter to compare the influence of wheel track distribution on the equivalent force amplitude. The equivalent stress amplitude is calculated according to equation (2) shown as followed:
\[ \Delta \sigma_{eq} = \left( \sum p_x \Delta \sigma^x \right)^{1/m} \]  

In the equation \( \Delta \sigma_{eq} \) is the stress amplitude induced by load at the transverse position \( x \); \( p_x \) is the probability of transverse distribution of load.

**Table 6 Equivalent stress amplitude under different transverse probability distributions.**

| Loading modes | Loading of influence line | Standard deviation \( \sigma \) considering fatigue stress influence surface model (mm) |
|---------------|---------------------------|--------------------------------------------------------------------------|
|               | 80 | 100 | 200 | 225 | 300 | 400 | 500 | 600 |
| A Equivalent stress (MPa) | 95.01 | 87.51 | 85.47 | 78.38 | 76.94 | 72.91 | 68.22 | 64.31 | 61.06 |
| Stress reduction | - | 0.92 | 0.90 | 0.82 | 0.81 | 0.77 | 0.72 | 0.67 | 0.64 |
| B Equivalent stress (MPa) | 33.13 | 30.85 | 29.95 | 26.48 | 25.80 | 24.07 | 22.30 | 20.95 | 19.87 |
| Stress reduction | - | 0.93 | 0.90 | 0.80 | 0.78 | 0.73 | 0.67 | 0.63 | 0.60 |

It can be seen from the calculation results in Table 6 that the effects change rate of different transverse probability distributions on different fatigue details are almost the same. The equivalent stress amplitude obtained from the transverse load distribution given in China's *Specification of Steel Bridge* and Eurocode is 10% different from that obtained from the distribution probability in BS5400, which is more than 20% different from the measured vehicle stress amplitude. Adopting the China's *Specification of Steel Bridge* can ensure a certain degree of safety in anti-fatigue design, but the influence of lateral probability distribution of wheel track on fatigue details near wheel load should not be neglected in fatigue evaluation. If the probability distribution of load is considered for the study of fatigue performance, the reduction coefficient can be introduced to calculate the equivalent stress. The reduction coefficient of China's *Specification of Steel Bridge*, BS5400 and the distribution of traffic flow measured in China can be 0.9, 0.8 and 0.7 respectively.

5. Conclusion

The sensitivity of different load models to fatigue effect is discussed by collating and comparing the fatigue rules in JTG D64-2015 of China, Eurocode of Europe, BS5400 of UK and AASHTO of America, pointing out the deficiency of fatigue rules in current China's *Specification of Steel Bridge* and the direction of amendment.

(1) The effect of wheel load distribution on the stress influence surface of different fatigue details is more significant. It is suggested that the fatigue load model IV in Eurocode should be consulted to formulate the corresponding regulations based on the statistics and classification of wheel load aspect ratios in China.

(2) The diffusion effect of pavement on wheel load directly affects the results of fatigue calculation. It is disadvantageous for fatigue evaluation to refer to the specification of concrete bridge to introduce 45° diffusion angle, so it is suggested that the 26.5° diffusion angle of epoxy asphalt concrete pavement should be taken into account with reference to BS5400.

(3) The fatigue load vehicle model III of China's *Specification of Steel Bridge* is more suitable for fatigue assessment of steel bridges of China than the load vehicle model in AASHTO. Under the increasing load environment, the safety factor should be properly introduced into the fatigue vehicle model.

(4) The transverse probability distribution of the wheel track has a significant effect on the fatigue detail stress state, and the safety of more than 10% can be achieved by referring to the China's *Specification of Steel Bridge*. In fatigue assessment, the influence of transverse probability distribution on fatigue details near wheel load should be considered. In order to simplify the influence of wheel lateral distribution on fatigue effect, the reduction coefficient can be introduced.
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