FATIGUE EVALUATION OF HOT SPOT STRESS IN FATIGUE VULNERABLE AREA OF BRIDGE DECK STRUCTURE BASED ON THERMAL ENERGY MODELLING

by

Fangqin ZHAO [a*] ***and Qinghua LIAO*** [b]

[a] Anhui Institute of Public Security Education, Hefei, Anhui, China
[b] Tongling University, Tongling, Anhui, China

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The paper takes a Yangtze River bridge as the object, establishes a finite element model of the highway orthotropic steel deck structure, calculates and analyzes the fatigue stress of specific structural details based on the hot spot stress method, and obtains the fatigue vulnerable area of this type of bridge deck structure. Based on the bridge's actual use, the thesis calculates and evaluates the fatigue life of the typical welding details of the bridge deck based on the American Highway Bridge Design Code. The results show that the fatigue stress amplitude calculation of the five types of fatigue vulnerable structure details under the Fatigue I and Fatigue II limit states. The values are all less than the allowable value, and the fatigue life meets the design requirements.

Key words*: highway bridge, orthotropic steel bridge deck, fatigue stress, hot spot stress, fatigue assessment*

Introduction

The road orthotropic steel bridge deck is composed of cover plates, longitudinal ribs, and beams. Because the in-plane stiffness is different in the mutually perpendicular directions, resulting in the force's orthotropic behavior, it is called orthotropic steel deck (OSD). The orthotropic steel bridge deck has lightweight, high rigidity, high bearing capacity, and a wide application range. It can participate in the joint force as a part of the main girder, so it has been widely used in bridge engineering. Due to the complex structural stress, the difficulty of controlling welding defects, and the direct bearing of vehicle dynamics, the OSD structure's fatigue cracking has become the main reason affecting the normal use of such bridges. Many scholars at home and abroad have conducted a series of studies on this. Some scholars have carried out experimental research on the fatigue characteristics of highway orthotropic steel bridge decks with open longitudinal ribs. Some scholars have carried out a fatigue reliability analysis on Paderno highway bridges to obtain the remaining fatigue life of the structure. Some scholars have analyzed the fatigue cracks of OSD formation, and expansion have been studied. Some scholars have researched OSD fatigue performance, fatigue checking and other related issues [1]. This paper takes a Yangtze River bridge as an engineering example, establishes a finite element model of the steel bridge deck, and conducts research and analysis on the fatigue stress and fatigue life evaluation of highway orthotropic steel bridge deck.

* Corresponding author, e-mail: zhaofq1981@sina.com

Highway orthotropic steel bridge deck structure

The main bridge of the Yangtze River Bridge studied in the thesis is a six-span continuous steel truss arch bridge. The main bridge structure is shown in fig. 1. In this picture, the steel truss girder and steel truss arch of the main bridge structure of the Yangtze River Bridge is composed of three rows of main trusses with the same spacing (2×15 m). The joints of the main truss are arranged with one large beam, each with two large beams. Three small beams are arranged between. A certain Yangtze River Bridge is a typical highway OSD structure. Two inverted *T*-shaped longitudinal beams are arranged under the track of a single line, and the intersection of the crossbeam web and the *U*-rib and the inverted *T*-shaped longitudinal beam is opened. The thickness of the cover is 16 mm. The webs of the inverted *T*-shaped longitudinal beams are 12 mm thick, 472 mm high, and the flanges are 12 mm thick and 240 mm wide [2]. The *U*-rib is 6 mm thick, 260 mm high, and 300 mm wide at the top. The large beam's web is 18 mm thick and 2400 mm high and the web of the small beam is 18 mm thick and 1376 mm high.

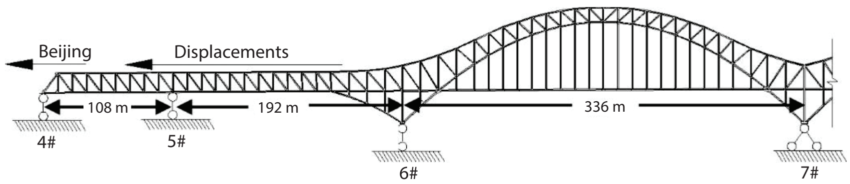

Figure 1. The structure of the main bridge of the Yangtze river bridge

Life assessment method of an orthotropic steel bridge deck

Fatigue analysis theory

From the perspective of engineering application, the fatigue analysis and evaluation methods of steel bridges mainly include three categories: structural classification, hot spot stress method, and fracture mechanics method. The structural classification method uses nominal stress amplitude for fatigue checking. The hot spot stress method is used for joint welding toe the surface stress is evaluated to analyze the local stress of potential fatigue welds. The fracture mechanics method is based on crack propagation and fracture to predict the remaining fatigue life of the structure. This article uses the hot spot stress method [3]. The local stress at the weld toe includes all the structural detail's stress concentration but does not include the stress concentration caused by the local weld shape. Affected by the notch effect, the stress gradient near the weld toe is very high. We usually use extrapolation calculate the local structural stress:

$$\sigma_{hs} = 1.5\sigma_1 - 0.5\sigma_2 \tag{1}$$

where σ_{hs} is the hot spot stress, σ_1, σ_2 – the stress at a distance of $0.5t$ and $1.5t$, respectively, from the weld toe and perpendicular to the weld toe, and t – the thickness of the steel plate. Since the stress concentration factor considers the effect of the overall geometry, the hot spot stress method requires only a small number or even one S-N curve. The AASHTO stipulates: the hot spot stress method mainly adopts the C-type curve in the S-N curve of the nominal stress method, and some special nodes adopt the A-type curve. Because the anti-fatigue design of the orthotropic steel bridge deck is not involved in my country's highway and highway bridge specifications. The AASHTO code systematically regulates the anti-fatigue design of the orthotropic steel bridge deck. The fatigue research in this paper is based on the AASHTO code.

Fatigue limit state and design level

Fatigue limit state

The AASHTO code provides two fatigue design methods, namely infinite life design and finite life design, to solve Fatigue I and Fatigue II limit state, respectively. Because the bridge deck is mainly subjected to wheel load and needs to withstand millions or even tens of millions of times of wheel pressure, it is usually necessary to consider the infinite life design, and when the traffic volume is not large, the limited life design is more economical.

Design level of an orthotropic steel bridge deck

There are three main design standards for orthotropic steel bridge decks: firstly, only a small amount of structural analysis is required for the structural details that have been proven to have sufficient resistance through a large number of tests. The second is based on simplified 1-D or 2-D analysis and the panel details are accurately evaluated; only the nominal stress is considered in the calculation, and the local stress concentration is not considered. The third is to accurately quantify the stress of the typical structure of the steel bridge panel based on the refined 3-D analysis [4]. In the absence of reference cases, this article adopts design standards.

Fatigue load of highway orthotropic steel bridge deck

To study the bridge's OSD fatigue performance, scholars should usually first obtain the fatigue load spectrum of the bridge deck, use the rain flow method or the drained pool method to analyze the stress history to obtain each stress amplitude and its corresponding value. The fatigue performance of the steel bridge deck is then analyzed. At present, when the fatigue load spectrum of the bridge is not fully studied, the design live load can also be used for approximate analysis, and the calculation results are biased towards safety.

The ZK live load in our country's design code belongs to the lane load, which is used to analyze the overall structure of the bridge and check whether the strength and stiffness of the structure meet the requirements under the design load. The fatigue study focuses on the local structure's details, and the vehicle load should be used as usual, but the ZK load cannot reflect the actual operating conditions of the bridge vehicles in this paper [5]. Therefore, based on the analysis of the actual operating vehicle parameters of the Yangtze River Bridge, a new high speed standard fatigue vehicle is obtained, which can provide a reference for future fatigue research.

The fatigue load factor depends on the standard fatigue load. The fatigue load factors of the two limit states in the fatigue design provisions of AASHTO on OSD panels and joints are $\gamma_{\mathrm{I}} = 1.50$ and $\gamma_{\mathrm{II}} = 0.75$, respectively. By analyzing the fatigue stress amplitude spectrum monitored in the actual project, it is found that the State I load factor originally suitable for the main beams, beams, truss rods, and other integral components cannot be safely applied to the design of some OSD components [6]. Research shows that compared with the main girder of a standard bridge, the experiment should increase the ratio of the maximum stress amplitude to the effective stress amplitude in the OSD structure design, so an additional correction factor of 1.5, namely 1.5×1, needs to be multiplied. For the detailed structure near the beam opening and the detailed structure of the part connected to the cover, State I load factor is 2.25. Besides, considering the dynamic effects under traffic loads, we increase all loads' impact coefficients by 15%.

Fatigue resistance calculation

Infinite life design

This type of design corresponds to the fatigue limit State I, and the maximum allowable fatigue stress amplitude $\Delta\sigma$ satisfies $\Delta\sigma = (\Delta\sigma)TH$, where $(\Delta\sigma)TH$ is the stress threshold of the S-N curve, and the fatigue stress thresholds of the A and C structures are 165.5 MPa and 69 MPa, respectively.

Limited life design

This type of design corresponds to the fatigue limit State II, and the maximum allowable fatigue stress amplitude $\Delta\sigma$ is determined:

$$(\Delta\sigma)_n = \left(\frac{A}{N}\right)^{1/3} \text{ or } (\lg A - \lg N) \tag{2}$$

where $N = 365 \times 100 \times n \times (ADTT)SL$, n is the number of cycles of stress amplitude generated by each vehicle, (ADTT)SL – the daily average traffic volume of a single lane, A – the constant related to the detail category. The constants in the structural details of Type A and Type C are $8177 \cdot 10^9$ MPa and $1439 \cdot 10^9$ MPa, respectively.

Evaluation method steps based on the S-N curve

The fatigue calculation is mainly aimed at the five structural nodes that are prone to fatigue cracks in the road orthotropic steel bridge deck structure, fig. 2, which are the longitudinal beam-cover, (SD), node, the longitudinal beam-cross beam (SF) node, U-rib-cover (RD) node, U-rib-beam (RF) node, and beam opening node.

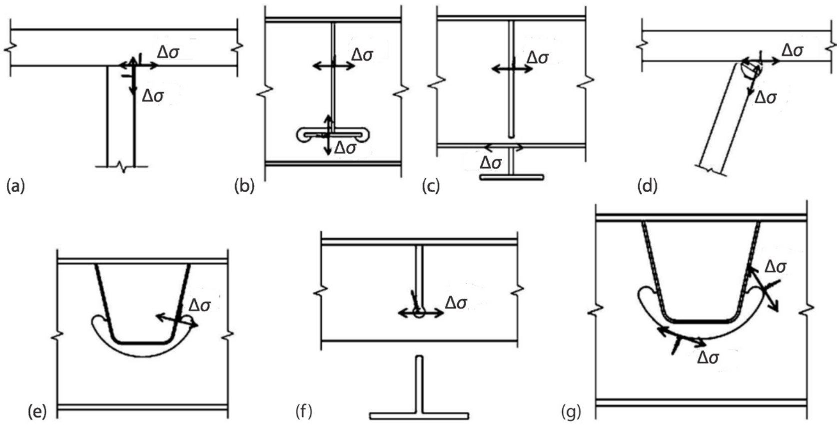

Figure 2. Fatigue crack locations of five typical structural details; (a) – SD node, (b) – SF node-beam, (c) – SF node-longitudinal beam, (d) – RD node, (e) – RF node-beam, (f) – RF node-longitudinal rib, and (g) – measure the opening node

Determine n

The n is the number of cycles of stress amplitude change caused by a single-vehicle passing through, which needs to be determined in conjunction with the vehicle's number of wheels. The structural details (SD node, RD node) connected to the cover plate directly bear the wheel load, and the influence line of this type of node is relatively short. The value of n is determined by the number of wheels of the passing vehicle. Consider the formation of eight vehicles. The row of wheels that is, $n = 8 \times 2 \times 2 = 32$. The structural details that are not connected to the cover plate (SF nodes, RF nodes, beam opening nodes) do not directly bear the wheel load, and the influence line of such nodes is relatively long [7]. According to the AASHTO specification, the front and rear wheels' passing times can be reduced from 2 to 1, that is, $n = 8 \times 2 \times 1 = 16$.

Except for the five types of structural details that need to be focused on in fatigue research, the method for determining n in other details is similar.

Estimated (ADTT) SL

The method of determining (ADTT) SL in this paper is based on the actual number of Beijing-Shanghai high speed rail passes provided by China's highway network, and a more reasonable (ADTT) SL value is 60.

Calculate the number of fatigue actions

According to the number of vehicles in a single day and the bridge's design life, the minimum number of fatigue load actions, N, required for the steel bridge deck to meet the design and use requirements is calculated.

Determine the fatigue allowable stress amplitude

According to the number of fatigue actions, N, the fatigue allowable stress amplitude of each structural detail is calculated through the specification's S-N curve. According to the American Orthotropic Steel Bridge Deck Design Manual and the American Highway Bridge Design Code, the crossbeam part of the crossbeam opening node is Class A structural details, and the rest are Class C structural details.

Calculation of hot spot stress amplitude

The finite element model can use shell elements (not considering the weld's geometric size) or volume elements (considering the geometric size of the weld) and establish a fine mesh model and a coarse mesh model as needed. The corresponding stress extrapolation area should meet the specification requirements. The hot spot stress amplitude needs to consider the load factors under different fatigue limit states.

Finite element model

Model size

The paper uses ABAQUS software to establish a two-line two-segment model of a Yangtze River bridge with a longitudinal length of 24 m and a lateral width of 15 m. It is composed of three large beams and six small beams. The specific dimensions of the model are shown in fig. 3. The material is Q370qE steel, the elastic modulus is 206 GPa, and the Poisson's ratio is 0.3. The model does not model the concrete ballast groove slab [8]. This approach is safer, but the concrete ballast groove slab's diffusion effect on the wheel load should be considered when the load is arranged.

Loads and boundaries

In this paper, the two-axle wheel pressure load of a high speed vehicle is used, and the rear wheel pressure of the front car and the front wheel pressure of the rear car are combined. The axle load of the vehicle is 1.5t. According to the size of the wheelbase, rails, and sleepers of the vehicle, the single wheel's surface spread to the bridge deck is a rectangle of 1310×1000 mm, so the uniform wheel load under the single wheel is 0.057 MPa. By comparing load conditions at different positions, it was decided to select two representative operating conditions for analysis: *Operating condition 1*, two axles of a bogie are symmetrically arranged concerning the large beam and *Operating condition 2*, the centerline of one axle is located just above the large beam, see fig. 3.

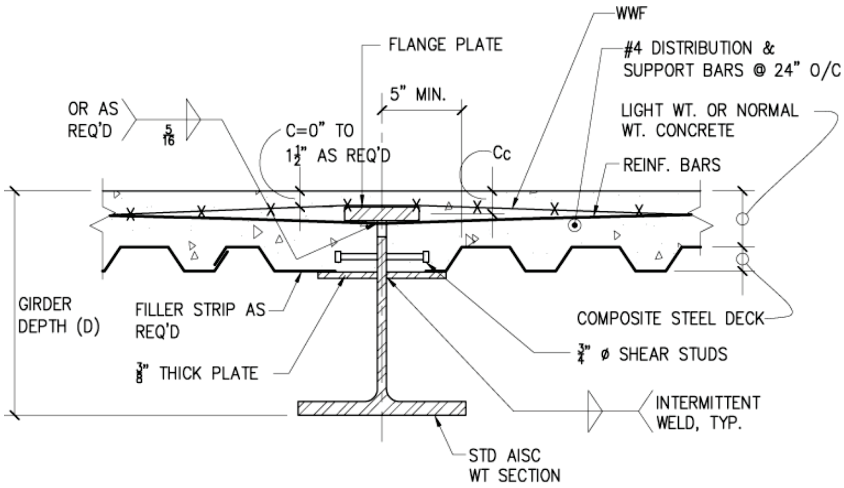

Figure 3. Bridge deck structure size

The paper establishes a mixed element finite element model of the overall structure of the bridge deck. By comparing the stress results of the two-line load and the single-line load, it is found that the stress difference under the two load forms is extremely small [9]. The reason is that the centerline of the two lanes is 5 m apart, which has exceeded the range of the influence line in the transverse direction, so the single lane load is used for analysis.

Meshing

The thesis uses shell elements for modelling: the 8-node shell element S8R is used for the stress concentration area between the large middle beam and the two small beams. The 4-node shell element S4 is used for other areas. The key research areas near the large beams are divided by fine grids. At the stress positions that need to be extracted, the grid size is divided according to the International Welding Association (IIW) requirements on the size of the stress extrapolation unit. The other areas are divided by coarse grids.

Stress analysis and life assessment

Stress analysis

The SD node

Taking the SD node under working condition one as an example, the hot spot stress at the welding toe of the cover plate and the longitudinal beam web is calculated and analyzed. The plate's thickness is 16 mm, and the stresses in the direction perpendicular to the weld at a distance of $0.5t$ and $1.5t$ from the weld are extracted to be –23.790 MPa and –19.943 MPa, respectively. Stress extrapolation:

$$\sigma = 1.5\times\left(-23.790\right) - 0.5\times\left(-19.943\right) = -25.714 \text{ MPa} \tag{3}$$

Design according to Fatigue I:

$$\gamma(\Delta f) = 2.25\times1.15\times25.714 = 66.535 \text{ MPa} \tag{4}$$

Designed according to Fatigue II:

$$\gamma(\Delta f) = 0.75\times1.15\times25.714 = 22.178 \text{ MPa} \tag{5}$$

The plate's thickness is 12 mm, and the stresses in the direction perpendicular to the weld seam at a distance of $0.5t$ and $1.5t$ from the weld are extracted as 4.995 MPa and –1.927 MPa, respectively. Stress extrapolation:

$$\sigma = 1.5 \times 4.995 - 0.5 \times 1.927 = 6.529 \text{ MPa} \quad (6)$$

Design according to Fatigue I:

$$\gamma(\Delta f) = 2.25 \times 1.15 \times 6.529 = 16.894 \text{ MPa} \quad (7)$$

Designed according to Fatigue II:

$$\gamma(\Delta f) = 0.75 \times 1.15 \times 6.529 = 5.631 \text{ MPa} \quad (8)$$

Under the action of *working condition 1*, there are stress extremes in the welding toe of the SD node cover plate and the longitudinal beam web at the bridge deck A and B, as shown in fig. 4, and the SD node stress cloud diagram is shown in fig. 5. The stress direction is perpendicular to the weld.

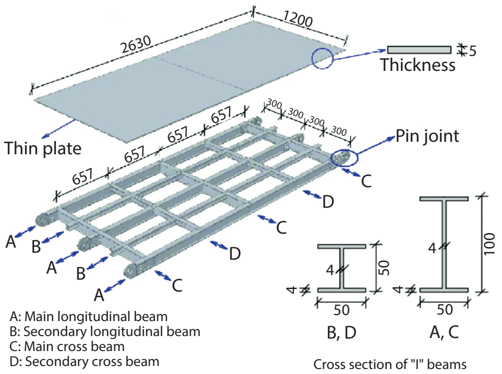

Figure 4. Stress analysis area

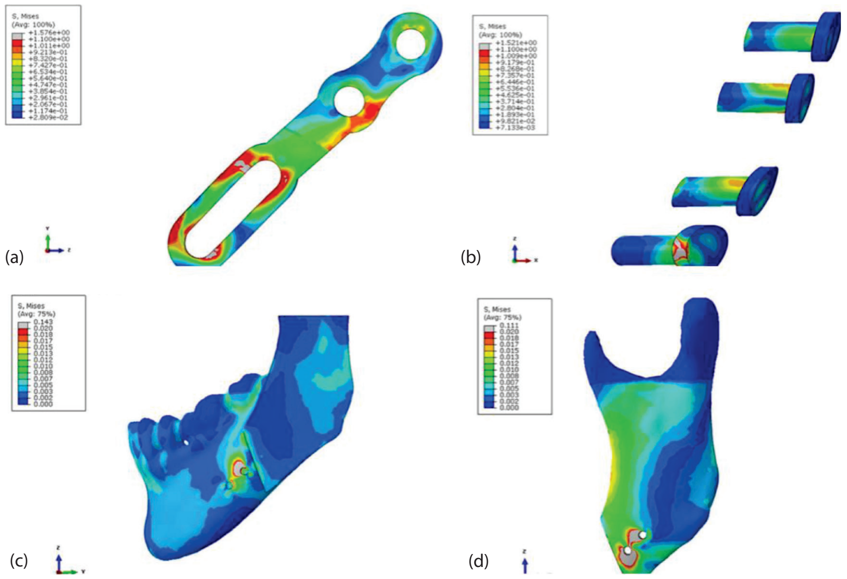

Figure 5. Stress cloud diagram of SD node: (a) sliding-plate, (b) four screws, (c) distal segment (buccal view), and (d) proximal segment

The SF node

Under the action of *working condition 1*, the vertical welds of the longitudinal webs of the SF joints of the bridge deck C and D and the horizontal welds of the lower flange of the longitudinal beams have stress extremes. The webs of the SF joints of the bridge decks E and F are vertical. Straight welds and horizontal welds have stress extremes. The stress cloud diagram is shown in fig. 6, and the stress direction is perpendicular to the weld.

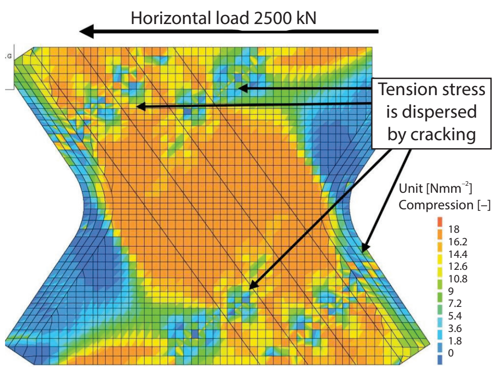

Figure 6. Stress cloud diagram of SF node

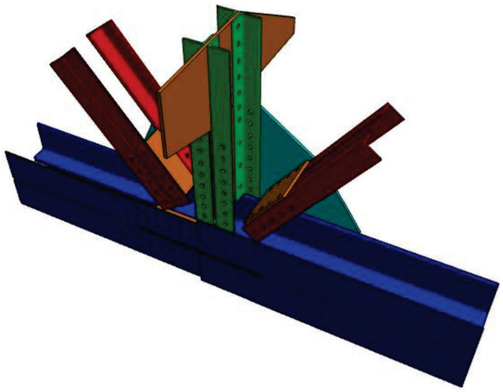

Figure 7. Stress cloud diagram of RD node

The RD node

Under the action of *working condition 1*, there are stress extremes at the weld toe and U rib of the RD node cover plate at the G and H parts of the bridge deck. The stress cloud diagram of the RD node is shown in fig. 7, and the stress direction is perpendicular to the weld.

Life assessment

Allowable fatigue stress amplitude

According to the AASHTO specification on the calculation of fatigue resistance, for the infinite life design of Fatigue I, the allowable value of fatigue stress amplitude for the details of type A is 165.5 MPa, and the allowable value of fatigue stress amplitude for the details of type C is 69 MPa. For the finite life design of Fatigue II, (ADTT) SL is estimated to be 60, where n is $8 \times 2 \times 2$, there are SD nodes and RD nodes. Where n is 8×2, there are SF nodes, RF nodes, and beam openings. Uribe position of the hole. Take the SD node as an example and calculate the allowable value of fatigue stress amplitude corresponding to Fatigue I and Fatigue II design:

– Fatigue I design

The SD node belongs to the C-type structure, so the allowable fatigue stress amplitude is 69 MPa.

– Fatigue II design

The constant

$$(\Delta\sigma)_n = \left(\frac{A}{N}\right)^{1/3} = \left(\frac{1439 \cdot 10^9}{70080000}\right)^{1/3} = 27.4 \text{ MPa}$$

corresponding to the SD node is $1439 \cdot 10^9$ MPa, the minimum number of fatigue load action A.

Evaluation results

Fatigue stress and life evaluation results are shown in tab. 1. It can be seen that under the two working conditions, the fatigue stress amplitudes of Fatigue I and Fatigue II of the five key nodes are all less than the allowable value. Based on this, it can be judged that the steel deck design of the Yangtze River Bridge meets the infinite life requirement.

Table 1. Fatigue stress and life evaluation results

	Construction details	Weld toe of the cover plate		Weld toe of the beam web	
	n	32			
	$N/10^4$	7008			
	Working condition	1	2	1	2
The calculated value of fatigue stress amplitude [MPa]	Fatigue I	66.5	57.1	16.9	14.1
	Fatigue II	22.2	19	5.6	4.7
Allowable fatigue stress amplitude [MPa]	Fatigue I	69			
	Fatigue II	27.4			
Whether to meet the design life	Unlimited life	Satisfy	Satisfy	Satisfy	Satisfy
	100 years of life	Satisfy	Satisfy	Satisfy	Satisfy

Conclusion

The paper takes a Yangtze River bridge as an example to establish a method for fatigue stress analysis and fatigue life evaluation of highway orthotropic steel bridge deck. A finite element model was established for the bridge deck structure with two lines and two segments, and the hot spot stress analysis under two load conditions was carried out. Combined with the SN curve of the AASHTO code, specific structural details' fatigue life was evaluated. The results showed that the steel deck the welding structure details meet the design requirements.

References

[1] Jung, B. H., *et al*., Fatigue Assessment of Very Large Container Ships Considering Springing Effect Based on Stochastic Approach, *Journal of Ocean Engineering and Technology*, *34* (2020), 2, pp. 120-127
[2] Wu, S., Study and Evaluation of Clustering Algorithm for Solubility and Thermodynamic Data of Glycerol Derivatives, *Thermal Science*, *23* (2019), 5, pp. 2867-2875
[3] Petrini, F., *et al*., Coupling Effects between Wind and Train Transit Induced Fatigue Damage in Suspension Bridges, *Structural Engineering and Mechanics*, *703* (2019), 3, pp. 311-324
[4] Wang, C. S., *et al*., Numerical Simulation of Distortion-Induced Fatigue Crack Growth Using Extended Finite Element Method, *Structure and Infrastructure Engineering*, *16* (2020), 1, pp. 106-122
[5] Putra, T. E., *et al*., Novel Way to Overcome Problems Arising in Strain Signal Measurements Leading to a Fatigue Failure Characterisation, *International Journal of Automotive and Mechanical Engineering*, *17* (2020), 3, pp. 8104-8115
[6] LI, X., *et al*., Research on Bridge Structural Health Assessment Based on Finite Element Analysis, *Tehnički vjesnik*, 27 (2020), 1, pp. 96-105
[7] Lemma, M. S., *et al*., Enhancement of the Life-Cycle Performance of Bridges Using High-Strength Steel, *Structure and Infrastructure Engineering*, *16* (2020), 4, pp. 772-786
[8] Wu, S., Construction of Visual 3-D Fabric Reinforced Composite Thermal Perfomance Prediction System, *Thermal Science*, *23* (2019), 5, pp. 2857-2865
[9] Feng, D., *et al*., Designation Principle and Method for Functionally Graded Composite Pavement, *Chinese Science Bulletin*, *65* (2020), 30, pp. 3270-3286

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