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Fatigue damage reliability analysis for Nanjing Yangtze river bridge using structural health monitoring data①

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Abstract: To evaluate the fatigue damage reliability of critical members of the Nanjing Yangtze river bridge, according to the stress-number curve and Miner's rule, the corresponding expressions for calculating the structural fatigue damage reliability were derived. Fatigue damage reliability analysis of some critical members of the Nanjing Yangtze river bridge was carried out by using the strain-time histories measured by the structural health monitoring system of the bridge. The corresponding stress spectra were obtained by the real-time rain-flow counting method. Results of fatigue damage were calculated respectively by the reliability method at different reliability and compared with Miner's rule. The results show that the fatigue damage of critical members of the Nanjing Yangtze river bridge is very small due to its low live-load stress level.

Key words: fatigue damage reliability evaluation; railway steel bridge; structural health monitoring; real-time rain-flow counting method

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1 INTRODUCTION

Steel bridges are very common in the world. According to Ref. [1], there are about 12 000 steel bridges on the Chinese railways. Most of them are more than 30 years old, which are over or near the design life and must be repaired, strengthened, or reconstructed to ensure safety considering the present and future-traffic needs. Because of the high cost of reconstruction and lack of fund, structural health monitoring and fatigue life assessment of the old steel bridges have become important and urgent issues. There have been a lot of researches on fatigue problem of steel bridge under variable-amplitude loading[2-5].

The Nanjing Yangtze river bridge(NYRB) located in Nanjing city crossing the Yangtze river, which carries both highway and railway traffic, was commissioned in 1968. The bridge serves as the main portion of the railway between Beijing and Shanghai. It consisted of three units of three-span-continuous truss with span length 160 m - 160 m - 160 m and simple supported truss with span length 120 m for its main spans[6]. Since the bridge has been serviced approximately for 36 years, its safety became a big concern to the government related. Therefore, the structural health monitoring system (SHMS) has been installed on the bridge to monitor its integrity, durability and reliability. This SHMS consists of sensor system, data acquisition and processing system, and structural monitoring condition assessment system. This monitoring system comprises a total of approximately 150 sensors, including accelerometers, strain gauges, displacement transducers, temperature sensors, weigh-in-motion sensors, anemometer and seismograph etc, installed permanently on the bridge[7,8].

In this study, the south unit of three-span-truss was investigated to estimate the remaining fatigue life under variable train loading. A total of 50 strain gauges were installed at main diagonal bracings, bottom chords, vertical posts, crossbeams and longitudinal girders of main cross-sections to measure strain induced by moving trains.

2 FATIGUE DAMAGE RELIABILITY ANALYSIS

2.1 *S-N* curve

Many fatigue specifications are based on stress-number (*S-N*) curve, which relates the fatigue life to the cycle-stress range and can be expressed in the following equation[9]:

$$N\Delta\sigma^{m}=C \tag{1}$$

or

$$m\lg\Delta\sigma+\lg N=\lg C \tag{2}$$

where N is the total number of constant-amplitude-stress cycles to failure; $\Delta\sigma$ is the constant amplitude tensile-stress range; C is the

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fatigue-strength coefficient and m is the fatigue-strength exponent within the range from 2 to 4.

2.2 Miner's rule

To consider the variable amplitude stress cycles induced by trains loading, the direct use of standard S-N curves is impossible. Miner[10] proposed a linear fatigue-damage accumulation model to consider partial-fatigue damage at the different stress-range levels. According to the model, the fatigue damage due to each stress range is proportional to the number of cycles of the particulate stress range. This linear damage-accumulation hypothesis, is commonly known as Miner's rule, and can be expressed as follows:

$$D = \sum_{i=1}^{k} \Delta\sigma_i = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{3}$$

where n_i is the number of stress-range level $\Delta\sigma_i$; N_i is the total number of cycles to failure, namely the fatigue life in constant-stress range $\Delta\sigma_i$; k is the stress level progression and D is the Miner's damage-accumulation index.

2.3 Fatigue damage reliability analysis

Transforming the Eqn. (1), we have:

$$\frac{1}{N} = \frac{\Delta\sigma^m}{C} \tag{4}$$

Substituting Eqn. (4) into Eqn. (3), the fatigue damage is again obtained:

$$D = \sum_{i=1}^{k} \frac{n_i \Delta\sigma_i^m}{C} = \frac{1}{C}\sum_n \Delta\sigma^m = \frac{1}{C}\sum_n S = \frac{S_{sum}}{C} \tag{5}$$

where $n = \sum n_i$, $S = \Delta\sigma^m$, $S_{sum} = \sum S$. If the number of data is reasonably large, the S_{sum} approximately follows a normal distribution in terms of the statistics, and the distribution parameters (mean $\bar{S}$ and deviation S^2) can be used into fatigue stress spectrum. Together with Eqn. (5), $n\,\bar{S}/C$ and $\sqrt{n}\,S_s/C$ can be regarded as the distribution parameters of D denoting the mean and standard deviation in normal distribution, respectively[11, 12].

3 STRESS-TIME HISTORY AND STRESS SPECTRUM

The considered portion, the cross-section and strain gauges layout of the Nanjing Yangtze river bridge in addition to the overall profile are shown in Fig. 1.

Fatigue damage is dependent on the nature of the stress-time history that is generated by the live loads on the bridge. Since the train-loads are greater than other live loads[13], the live loads of moving trains are only considered in this paper. The total number of trains traveling over the NYRB is almost 250 per day. Fig. 2 clearly shows the stress-time histories induced by a passenger train and the corresponding stress ranges obtained by real-time rainflow counting method of some critical members[14, 15].

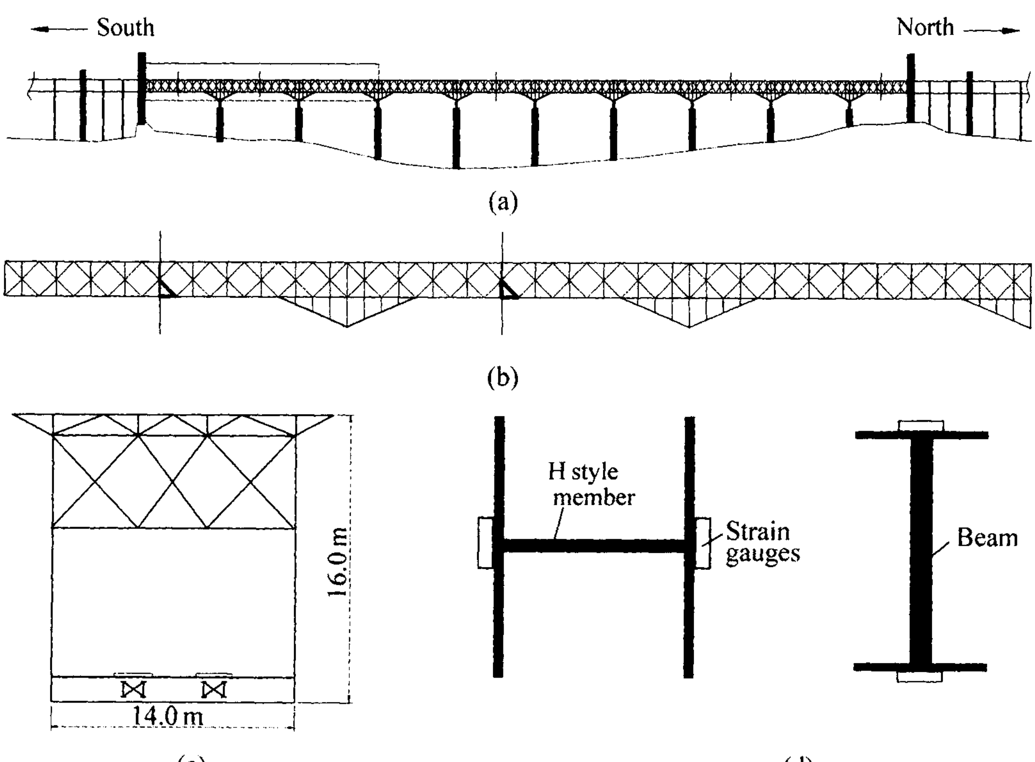

Fig. 1 Profile of Nanjing Yangtze river bridge

(a)—Overall profile; (b)—South portion of main span; (c)—Cross-section; (d)—Strain gauges layout

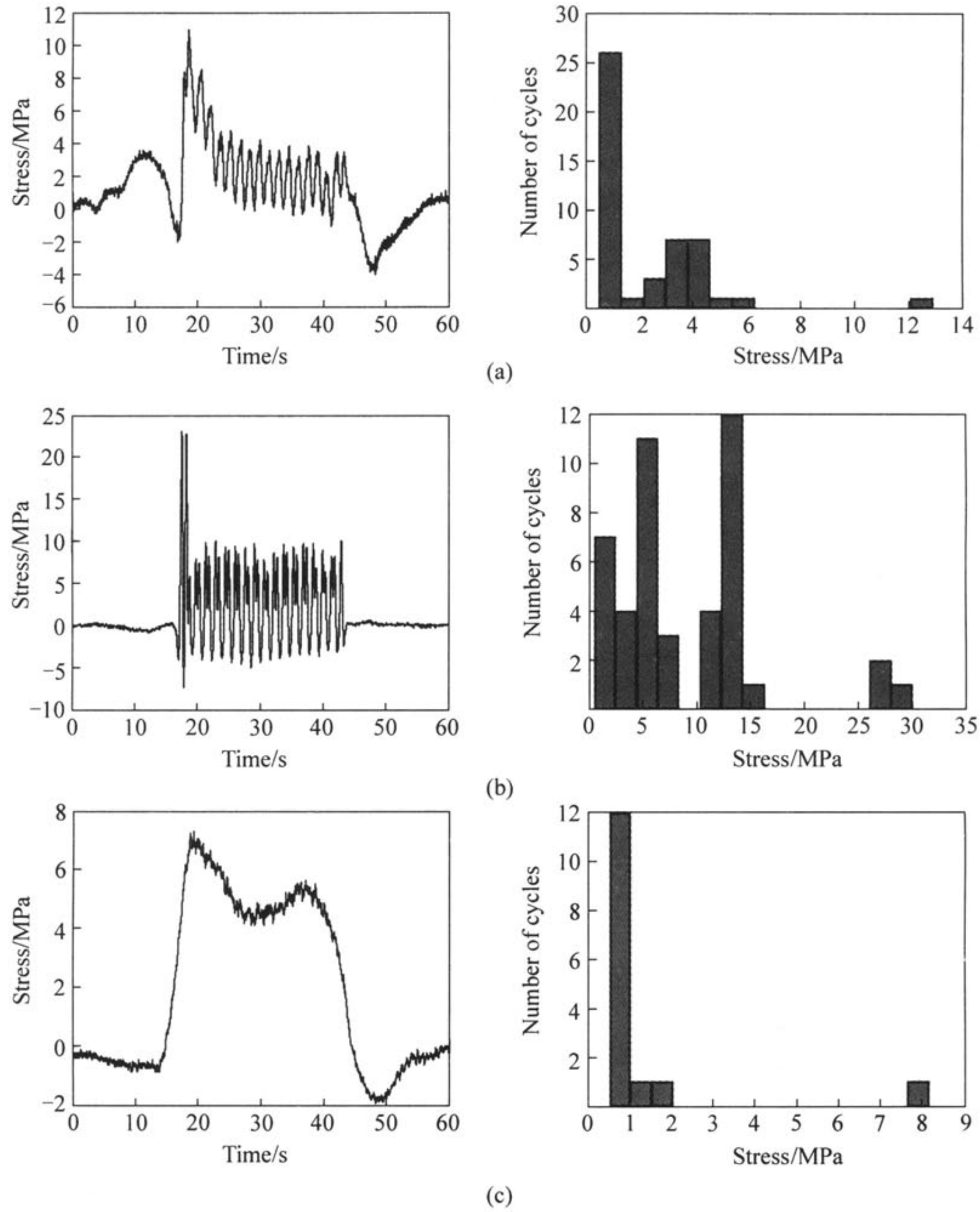

Fig. 2 Stress-time histories(left) and stress spectra(right) occurring at some critical members
(a)—Diagonal member; (b)—Longitudinal girder; (c)—Bottom chord

It should be mentioned that a lot of low stress cycles not induced by moving trains and less than the dead band have been reduced in the process of data analysis.

4 FATIGUE DAMAGE EVALUATION

Since it is difficult to cut fatigue test specimens from the members of the NYRB for some factors, and considering the material characteristics of the bridge, the proposed *S-N* curve parameters[16] are listed in Table 1. For the purpose of comparison, the parameters in BS5400 code[17] are also listed in Table 1.

With the database recorded by the online SHMS, a day (24 h) fatigue stress range generated by all trains passing over the bridge was obtained. Using the above methods, fatigue damage at some main members of the NYRB with different reliability was calculated and shown in Table 2, in which values based on Miner's rule are also given.

Table 1 Parameters of *S-N* curve

Method	C	lg*C*	*m*
Proposed	5.6338×10^{13}	13.750 8	4.0
BS5400 D	1.5189×10^{12}	12.181 3	3.0

Table 2 Comparison of fatigue damage results calculated by proposed method and B55400 code

Location	Method	Reliability/%			Miner's rule
		50.0	80.0	97.5	
Bottom chord	Proposed	1.1609×10^{-13}	3.7642×10^{-13}	7.1766×10^{-13}	3.8951×10^{-13}
	BS5400 D	4.3083×10^{-12}	1.3969×10^{-11}	2.6633×10^{-11}	8.1897×10^{-12}
Diagonal member	Proposed	7.1514×10^{-13}	1.1087×10^{-12}	1.6245×10^{-12}	3.0686×10^{-11}
	BS5400 D	2.6539×10^{-11}	4.1144×10^{-11}	6.0287×10^{-11}	2.4250×10^{-10}
Vertical post	Proposed	1.3298×10^{-12}	1.8524×10^{-12}	2.5373×10^{-12}	6.8455×10^{-11}
	BS5400 D	4.9349×10^{-11}	6.8742×10^{-11}	9.4162×10^{-11}	6.3954×10^{-10}
Longitudinal girder	Proposed	2.7882×10^{-12}	3.5973×10^{-12}	4.6580×10^{-12}	9.3721×10^{-10}
	BS5400 D	1.0347×10^{-10}	1.3350×10^{-10}	1.7286×10^{-10}	4.1284×10^{-09}
Cross beam	Proposed	7.9219×10^{-13}	1.0429×10^{-12}	1.3715×10^{-12}	1.3741×10^{-11}
	BS5400 D	2.9399×10^{-11}	3.8702×10^{-11}	5.0897×10^{-11}	1.9397×10^{-10}

5 CONCLUSIONS

1) Different members of the NYRB have different fatigue damage. The fatigue damage of longitudinal girder is greater than that of the other members. The results indicate that the fatigue damage of the NYRB main members is very small due to its low live-load stress level.

2) The difference of the fatigue values based on different methods is clear. It is very important to select the suitable method to evaluate the fatigue damage of a bridge. Since the material characteristic of the NYRB is close to the proposed curve, the values based on the proposed curve are more realistic to the bridge.

3) Since the trains loads are greater than other live loads, the stress-time history shows that it is reasonable and feasible to only consider the train live loads to evaluate the structure fatigue damage of the highway-railway bridges. Therefore, the online SHMS can only record real-time process and the stress data induced by moving trains, which can improve the level of automatization of structural health monitoring.

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