Research on High-Speed Train Load Spectrum and Bridge Load Effect Spectrum

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Abstract. Based on ANSYS finite element analysis software, a dynamic model of the Beijing-Tianjin intercity railway car-track-bridge system is established to analyze the dynamic response of the bridge under the normal high-speed double-track traffic conditions. Combined with the statistics of actual train operation, the bridge load spectrum represented by wheel/rail force is obtained. With the aid of the rain-flow counting method, the stress data of the weak part of the bridge span is equivalently converted into variable amplitude stress amplitude and the corresponding cycle times are obtained. In this way, the stress spectrum of the Beijing-Tianjin intercity railway bridge in the use reference period is estimated, which provides a certain reference basis for the life assessment of the in-service bridge and the reinforcement of weak parts in the future.

Keywords. Prestressed concrete beam, load spectrum, stress spectrum, rain-flow counting method.

1. Introduction
With rapid economic development, the application of inter-city high-speed rail has gradually become widespread. According to statistics, viaducts occupy a relatively high proportion of the load-bearing structure of intercity high-speed rail. For example, the proportion of Beijing-Tianjin intercity high-speed rail bridges is as high as 87.7%. However, with the gradual increase of driving speed and frequency of departure, the problem of axle vibration response and accompanying fatigue damage accumulation gradually becomes prominent.

In recent years, researchers have conducted in-depth research on the vibration response of vehicle bridges and achieved a series of results. Xia et al. [1] conducted on-site train dynamic load tests with a maximum speed of 321.5km/h and 290km/h on a 24 m multi-span prestressed concrete simply supported box girder on the Qin-Shen Passenger Dedicated Line. The results of the dynamic response of the car-bridge-beam under the action of the high-speed train are analyzed. Wang [2] used MATLAB software to establish a random vehicle load spectrum and calculated the dynamic response of the bridge superstructure to analyze the fatigue performance of the prestressed concrete beam under vehicle load. According to her analysis, under the vehicle load spectrum, the fatigue life of the bridge mainly depends on the fatigue life of the concrete material. Li et al. [3] compared the dynamic response results of 32 m simply supported T-beams calculated by three different vehicle-bridge dynamic response analysis methods based on the actual measured data of the bridge. Through a detailed analysis of the moving load spectrum, Li [4] establishes the relationship between the moving load speed and the extreme value response of the bridge's free vibration. Cui [5] established the finite element model of the vehicle bridge...
and the corresponding fatigue load spectrum, combined with the rain flow counting method and the S-N curve to estimate the fatigue life of the bridge structure.

Because the research on the load spectrum and load effect spectrum of bridge high-speed trains is still limited, this paper selects the most common 32 m simple-supported box girder of the Beijing-Tianjin intercity high-speed railway as the prototype beam and uses ANSYS finite element software to establish a three-dimensional simplified train-track-bridge model. Combining the statistical data of train operation characteristics and the rain flow counting method, the high-speed train load spectrum and the bridge load action spectrum are studied to provide a reference for bridge safety assessment.

2. The Train-Rail-Bridge Dynamic Model of Beijing-Tianjin Intercity Railway
This paper uses ANSYS finite element software vehicle, track and bridge to establish the model, and then assemble the vehicle-rail-bridge dynamic model and carry out the dynamic analysis under the two-line opposing driving condition.

2.1. The Bridge Model
The Beijing-Tianjin intercity railway bridge is dominated by 32 m prestressed concrete simply supported box girder. When building the finite element box girder model in ANSYS, the Beam188 element based on the Timoshenko beam theory was selected to establish an integral bridge element, and the second-stage dead load of the bridge was distributed to the corresponding bridge element as a uniform mass. Figure 1 below is a schematic diagram of the box girder mid-span section. Figure 2 shows the bridge finite element space calculation and analysis model.

2.2. The Vehicle Model
This paper uses the relevant parameters of the typical CRH3 "harmony" train model running on the Beijing-Tianjin intercity viaduct to establish the vehicle finite element model. The vehicle system can be divided into two main parts according to its connection mode: bogie and body. The bogie consists of side frames, supports, axles, wheels, and suspension systems. The suspension system is further divided into a first suspension system and a second suspension system. The first suspension connects the wheel and the bolster, and the second suspension connects the bolster and the body. When building the model in ANSYS, the body, bolsters, side frames, and axles all use beam elements (Beam188), the suspension system uses spring damping elements (Combin14), and the wheels use solid elements (Solid45). The vehicle model is shown in figure 3.
2.3. The Track Model
The Beijing-Tianjin Intercity Railway uses a longitudinally connected slab ballastless track. The steel rail transmits external loads (such as train loads, wind loads, etc.) to the bridge via fasteners, track plates, mortar layers, and base plates. In this paper, the CRTSII type ballastless track is selected when using finite element modeling. From top to bottom, it is mainly composed of steel rail (Solid45 element), fasteners, track plate, mortar layer (Combin14 element), and base plate (Shell193 element). Figure 4 shows a schematic diagram of the track finite element model.

2.4. The Model Contact and Assembly
This paper uses MPC technology to solve the assembly problem between two adjacent models, and the contact connection between the wheel and the rail is simulated by the displacement-contact method, to assemble the vehicle, track, and bridge models to form an overall dynamic model. Figure 5 shows a schematic diagram of the vehicle-rail-bridge finite element model, and figure 6 shows a schematic diagram of the finite element model under the condition of dual-track traffic. For detailed model modeling operations and verification of model correctness, please refer to the companion paper [6].

3. Load Spectrum of the Intercity High-Speed Rail Bridge

3.1. Characteristics of the Beijing-Tianjin Intercity Railway
The Beijing-Tianjin Intercity Railway was officially put into operation in August 2008, with a maximum speed of 350km/h, connecting the two cities of Beijing and Tianjin. The Beijing-Tianjin Intercity Railway has undergone many adjustments in terms of train speed. The whole journey is about 35 minutes, and the minimum train travel time interval is 3 minutes. Table 1 shows the statistics of the characteristics of train traffic on the Beijing-Tianjin Intercity Railway.
Table 1. Loading number of trains on Beijing-Tianjin Intercity Railway.

| Train type | Group-ing | Operating period | Daily operating volume/pair | Annual train throughput /train | Annual load action times ×10^4 | Axle load per train /t | Annual operating load ×10^6 t |
|------------|-----------|-----------------|-----------------------------|-------------------------------|--------------------------------|-----------------------|-----------------------------|
| CRH3 8     | 2008–2011 | 47              | 17155                       | 54.896                        | 480                            | 14.469                | 14.469                      |
| CRH3 8     | 2011–2018 | 98.5            | 71905                       | 115.048                       | 480                            | 34.514                | 34.514                      |
| CRH3 8     | 2018–2019 | 136             | 99280                       | 158.848                       | 480                            | 47.654                | 47.654                      |

3.2. The Load Spectrum of Ordinary High-Speed Conditions

Ordinary high-speed conditions refer to situations where the vehicle is traveling at 350 kilometers per hour, regardless of track irregularity and stiffness damage during use. According to previous studies [7], the train wheel-rail force conforms to the normal distribution, and the relevant parameters are determined by equations (1)–(3) [8]. Extract the sample wheel-rail force represented by the first axle of the second carriage for statistical analysis.

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \quad (1)
\]

\[
\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (2)
\]

\[
C_v = \frac{\sigma}{\bar{x}} \quad (3)
\]

In the above equation: \( \bar{x} \) — sample mean; \( n \) — sample size; \( x_i \) — i-th sample value; \( \sigma \) — sample standard deviation; \( C_v \) — sample coefficient of variation. The average value of the train wheel-rail force extracted in this simulation is 113.988 kN, the standard deviation is 17.480. The normal distribution form of the sample wheel-rail force is: \( X \sim N(113.988, 305.550) \).

The size of the sample grouping interval and the number of groups are selected according to the Sturgis empirical equation [9] and the frequency of each group is not less than 5, and the sample is finally determined to be divided into 8 intervals, with an interval distance of 15.531 kN. The occurrence probability of loads in different load intervals is calculated by the equation (4):

\[
P\{a_i < X < b_i\} = \Phi\left(\frac{b_i - 113.988}{17.480}\right) - \Phi\left(\frac{a_i - 113.988}{17.480}\right) \quad (4)
\]

where \( a_i, b_i \) — the upper and lower limits of the load-interval; \( P \) — the probability of the frequency in the ith interval. Normal distribution \( \chi^2 \) test:

\[
\chi^2 = \sum_{i=1}^{r} \frac{(n_i - np_i)^2}{np_i} \quad (5)
\]

where \( r \) — the number of interval groups; \( p_i \) — the probability of the frequency in the i-th interval; \( n \) — the total number of sample data; \( n_i \) — the actual number of occurrences of the frequency in the i-th interval Assuming that the sample data conform to the normal distribution, the confidence level is 95%, and the sample degree of freedom is \( f \), when \( \chi^2 < \chi_{0.05}^2(f) \), the null hypothesis is established, that is, the sample data conforms to the normal distribution. Otherwise, the null hypothesis is overturned.
### Table 2. Wheel-rail force simulation data and the total number of actions.

| Serial number | Wheel-rail force range/ kN | Number | Frequency | Probability | Total number of actions ×10^4 |
|---------------|---------------------------|--------|-----------|-------------|-------------------------------|
| 1             | (-∞, 65.370]              | 5      | 0.03876   | 0.0346      | 76331.72                     |
| 2             | (65.370, 80.902]           | 10     | 0.07752   | 0.0703      | 152663.44                    |
| 3             | (80.902, 96.433]           | 17     | 0.13178   | 0.1408      | 259527.848                   |
| 4             | (96.433, 111.965]          | 30     | 0.23256   | 0.2052      | 457990.320                   |
| 5             | (111.965, 127.497]         | 27     | 0.20930   | 0.2550      | 412191.288                   |
| 6             | (127.497, 143.028]         | 20     | 0.15504   | 0.1596      | 305326.88                    |
| 7             | (143.028, 158.560]         | 12     | 0.09302   | 0.0871      | 183196.128                   |
| 8             | (158.560, +∞]             | 8      | 0.06202   | 0.0474      | 122130.752                   |

Under ordinary high-speed working conditions, the fatigue load interval, frequency, and the number of actions generated by the train passing the bridge at 350 kilometers during the bridge design reference period are shown in Table 2. After calculation, the degree of freedom of the sample data is 5, looking up the normal distribution table: \( \chi^2 = 2.4112 < \chi^2_{0.05}(5) = 11.070 \).

### Table 3. Statistical results of load spectrum.

| Single shaft dead weight /kN | Mean wheel-rail force /kN | Wheel-rail force standard deviation | Wheel-rail force Dynamic coefficient /% | Probability | Wheel-rail force Dynamic coefficient /% | Probability |
|-----------------------------|--------------------------|-----------------------------------|----------------------------------------|-------------|----------------------------------------|-------------|
| 125.44                      | 113.988                  | 17.480                            | 131.468                                | 85.3098     | 166.428                                | 99.8900     |

From the statistical results in Table 3, it can be seen that when considering the single mean square error, the wheel-rail force dynamic coefficient is 1.153, and the probability is 85.31%; when considering three times the mean square error, the dynamic coefficient is 1.327, and the probability is 99.89%. In this case, to ensure driving safety, it is recommended that the power factor adopts 1.4.

### 4. The Load Effect Spectrum of Intercity High-Speed Railway Bridge

#### 4.1. The Rain-Flow Counting Method

The rain flow counting method proposed by British engineers Matsui Ki and Endo [10] is widely used in engineering to estimate fatigue life. The train passing through the elevated bridge produces a random stress time history response on the beam, which needs to be equivalently converted into a variable amplitude or constant amplitude fatigue stress spectrum using the rain flow counting method. The rain flow counting method assumes that the structural damage caused by the cycle of small stress levels can be incorporated into the damage caused by the cycle of large stress levels. Figure 7 shows the schematic diagram of the rain-flow counting method.
The rain-flow counting process is as follows: (1) Select the peak and valley values of the stress time history at the extracted fatigue key points. Figure 8 shows the program for extracting peak and valley values using Matlab software; (2) The peak and valley value sequence is counted in a full cycle according to the counting rules, and then the remaining divergence-convergence sequence is changed. Mean half-cycle counting; (3) Finally, the half-cycles with the same mean value and range are merged into a full-cycle, and combined with the previous full-cycle classification to complete the rain flow count of the entire time history; (4) Extract all the cycles and record each Draw a histogram of the amplitude and mean of.

4.2. The Load Effect Spectrum of Bridges under Ordinary High-Speed Conditions
According to the companion paper [5], the stress response at the bottom plate of the bridge is the largest, that is, the weak part of the beam. Therefore, the stress response time history value in the middle of the floor is selected, and the load effect spectrum and the corresponding cycle number are obtained by the rain-flow counting method, as shown in figure 9 and figure 10.

5. Conclusion
(1) According to the characteristics of the train and the finite element analysis, the load spectrum of the bridge under the train is obtained. According to the results of considering the different mean square errors, in order to ensure driving safety, it is recommended that the dynamic coefficient adopts 1.4.

(2) Combining the finite element analysis data and the rain flow counting method to obtain the load effect spectrum of the weak part of the bridge span can provide reference and basis for the fatigue cumulative damage analysis and safety assessment of the bridge.
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