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Influence of the Randomness of Longitudinal Resistance of Ballast Bed on Track-Bridge Interaction

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Abstract

To get the influence of the randomness of longitudinal resistance of ballast bed (LRBB) on track-bridge interaction, the statistical law of LRBB was studied with existing test data and the Shapiro-Wilk test. Based on the principle of track-bridge interaction, a rail-sleeper-bridge-pier integrated simulation model that could consider the randomness of LRBB was established. Taking a continuous beam bridge for the heavy-haul railway as an example, the effect of the randomness of LRBB on the mechanical behavior of continuous welded rail (CWR) on bridges under typical conditions was carefully examined with a random sampling method and the simulation model. The results show that the LRBB corresponding sleeper displacement of 2 mm obeys a normal distribution. When the randomness of LRBB is considered, the amplitudes of rail expansion force, rail bending force, rail braking force and rail broken gap all follow normal distribution. As the standard deviations of the four indexes are small, which indicates the randomness of LRBB has little effect on track-bridge interaction. The distributions of the four indexes make it possible to design CWR on bridges with the limit state method.

Keywords

Continuous Welded Rail, Track-Bridge Interaction, Longitudinal Resistance of Ballast Bed, Normal Distribution

1. Introduction

Ballasted track is the traditional structural form of track in my country. It has the advantages of low construction cost, good drainage performance and easy maintenance and repair. LRBB and evolution rules are extremely important to ensure the safety of train operations [1]. In particular, the reasonable value and distribution law of LRBB directly affects the track-bridge interaction of CWR.

Many researchers have performed experiments and numerical simulations to study LRBB. Gao *et al.* [2] pointed out the influence of ballast rheology characteristic on the testing of LRBB, and proposed the new testing method of LRBB considering the rheology characteristic. Esveld [3], Yang *et al.* [4], Yang *et al.* [5], Antonio *et al.* [6], obtained the LRBB with in-situ tests and proposed the recommended value of LRBB. Zakeri *et al.* [7], Jing *et al.* [8], Alizadeh *et al.* [9] conducted a series of resistance tests to investigate the influence of test method, crib level of ballast and types of sleepers on LRBB. Xiao *et al.* [10], Liu *et al.* [11] conducted cyclic loading experiments to analyze the effect of loading rates and displacement amplitude on LRBB with a full-scale test model of ballasted track. Liu *et al.* [12] tested the LRBB under different temperature and humidity conditions and obtained the performance evolution patterns through data fitting. Nobakht *et al.* [13] studied the effect of vertical load on LRBB with a three-dimensional finite element model. Zeng *et al.* [14] [15] [16] [17] established a three-dimensional model for the ballast bed and sleeper based on discrete element theory to study the influence of ballast bed density, track panel and sleeper bottom pressure on LRBB. The researches provide assistance in understanding the mechanism of LRRR, determining the parameters of LRBB and structural optimization of ballast bed. The above research also indicates that LRBB has significant randomness because of the numerous influencing factors.

There also are many researchers who studied the influence of LRBB on track-bridge interaction. Wang *et al.* [18] discussed the effects of different forms of LRBB on track-bridge interaction of CWR on bridges. Xie *et al.* [19] proposed an iterative calculation method for constructing track frames and analyzed the laws of track-bridge interaction under the longitudinal resistance of track frames. Ruge *et al.* [20] [21] [22] [23] analyzed the influence of load history on LRBB and derived the relationship between restoring force of LRBB and relative displacement, and then the method was used to determine the effect of load. Xie *et al.* [24] put forward an approach to reconstruct the displacement-force of LRBB to study to impacts of initial internal force and geometric nonlinearity of suspension bridge on track-bridge interaction. However, the randomness of LRBB has been ignored in these studies and its influence on track-bridge interaction is also unclear.

Based on the aforementioned analysis, this paper defines the distribution of LRBB, and proposes a simulation model to study the effect of randomness of LRBB on track-bridge interaction. Further, the obtained rules can provide support to the design of CWR on bridges with a limit state method.

2. Longitudinal Resistance of Ballast Bed

Using the existing test data of LRBB from the code [25], the LRBB with sleeper displacement of 2 mm is shown in **Figure 1**.

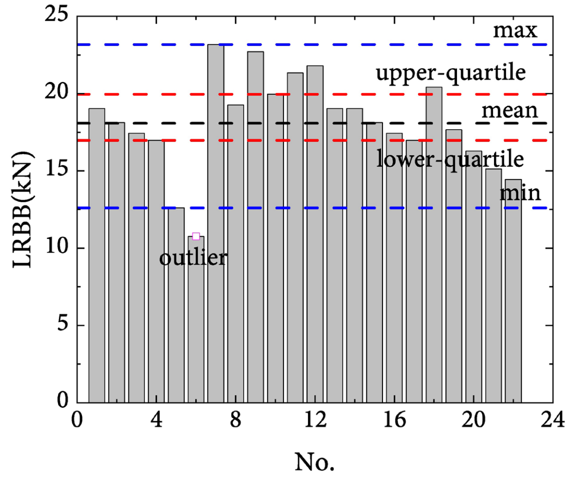


Figure 1. Statistical results of LRBB.

From the results of **Figure 1**, it can be seen that the maximum, minimum and mean values of LRBB are 23.18 kN, 12.61 kN and 18.07 kN, respectively. The test data of 10.77 kN is outlier data according to the upper and lower quartiles. After removing the outlier data from the overall sample, the Shapiro-Wilk test is performed. The test statistic W and p are 0.983 and 0.958, which indicates the LRBB obeys normal distribution. **Figure 2** shows the Q-Q plot for normal distribution test, which also indicates that the test data follow normal distribution, the mean and standard deviation of which are 18.43 kN and 2.66 kN.

3. Continuous Welded Rail Analysis Model on the Bridge

3.1. Model Establishment

Based on the principle of track-bridge interaction, a rail-sleeper-bridge-pier integrated simulation model illustrated in **Figure 3** is established [26].

The rail and sleeper are simulated with space beam elements. The longitudinal resistance of fasteners and LRBB are simulated by nonlinear spring elements. The longitudinal resistance of fastener is greater than the LRBB, and its influence on track-bridge interaction indicates minimal impact. So the randomness of the longitudinal resistance of fastener is not considered which means the longitudinal resistances of fasteners in the simulation model are equal. The nonlinear spring elements used to simulate the LRBB have different displacement-force curve to consider the randomness of LRBB. The beam element contains the cross-sectional characteristics of bridges, and the rigid arm element characterizes the bending deformation of the upper and lower flanges with reference to the neutral axis. The abutments and piers are simplified as linear spring elements. No less than 150 m of subgrade is established at both sides of the bridge abutments to reduce the influence of boundary conditions.

3.2. Calculating Parameters

In order to highlight the impact of LRBB on track-bridge [27], a span of (40 + 3

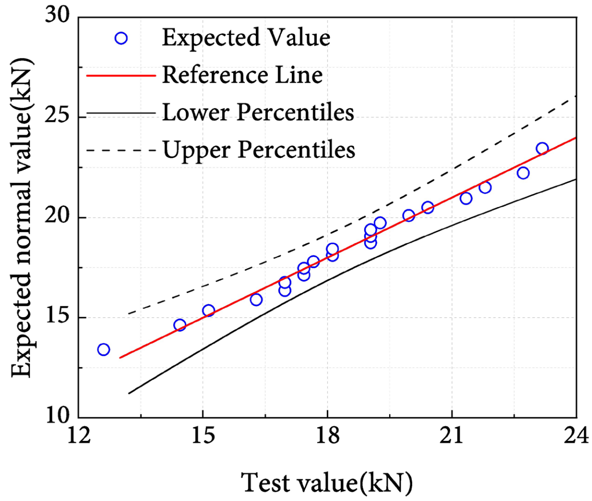


Figure 2. Q-Q plot.

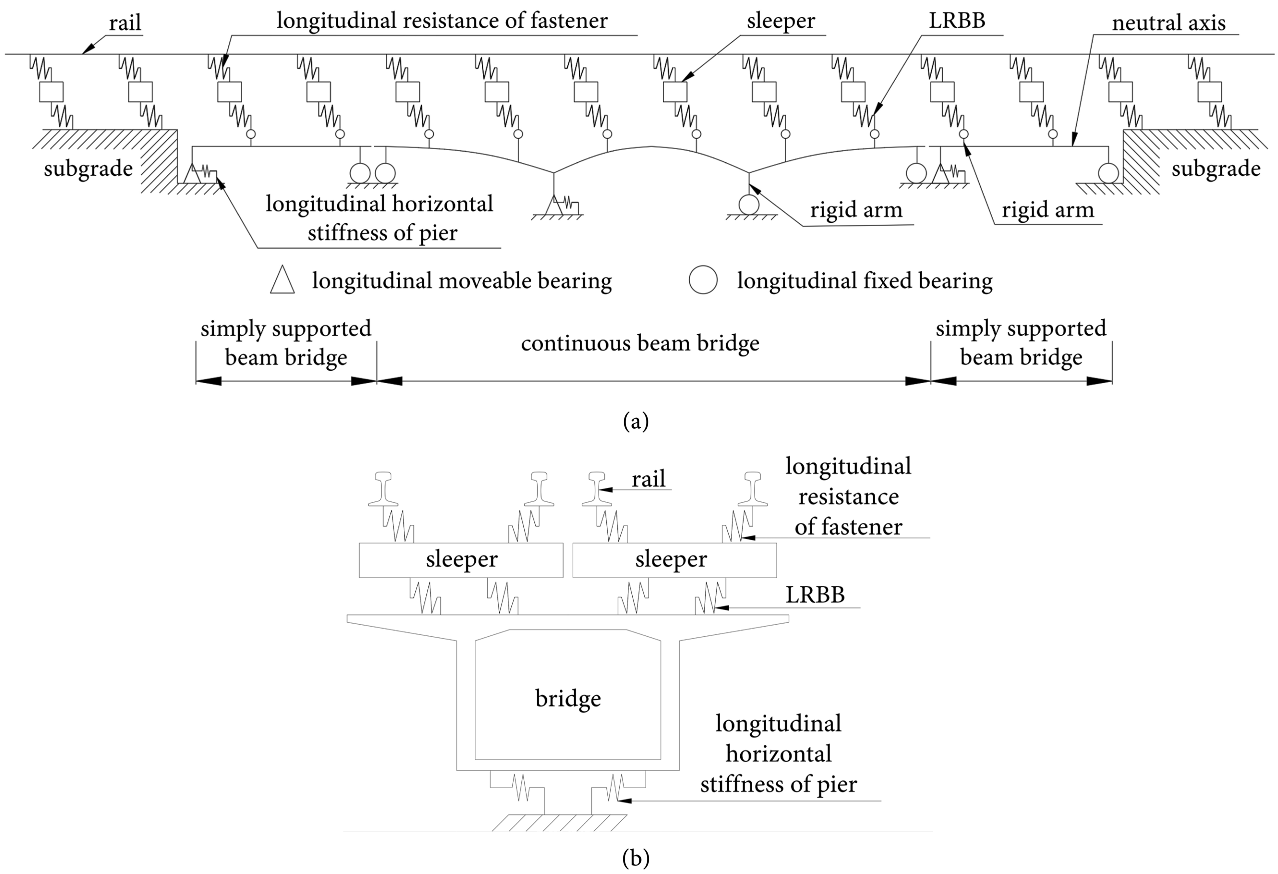


Figure 3. A rail-sleeper-bridge-pier integrated simulation model. (a) Profile view; (b) Cross-section view.

× 72 + 40) m for a heavy-haul railway is taken as an example. **Figure 4** shows the cross-sectional parameters of the continuous beam bridge.

Five-span 32 m concrete simply supported beam bridges are laid on the left and right side of the continuous beam bridge. The longitudinal stiffness of abutments and piers for simply supported bridges are set to 3000 kN/cm and 350

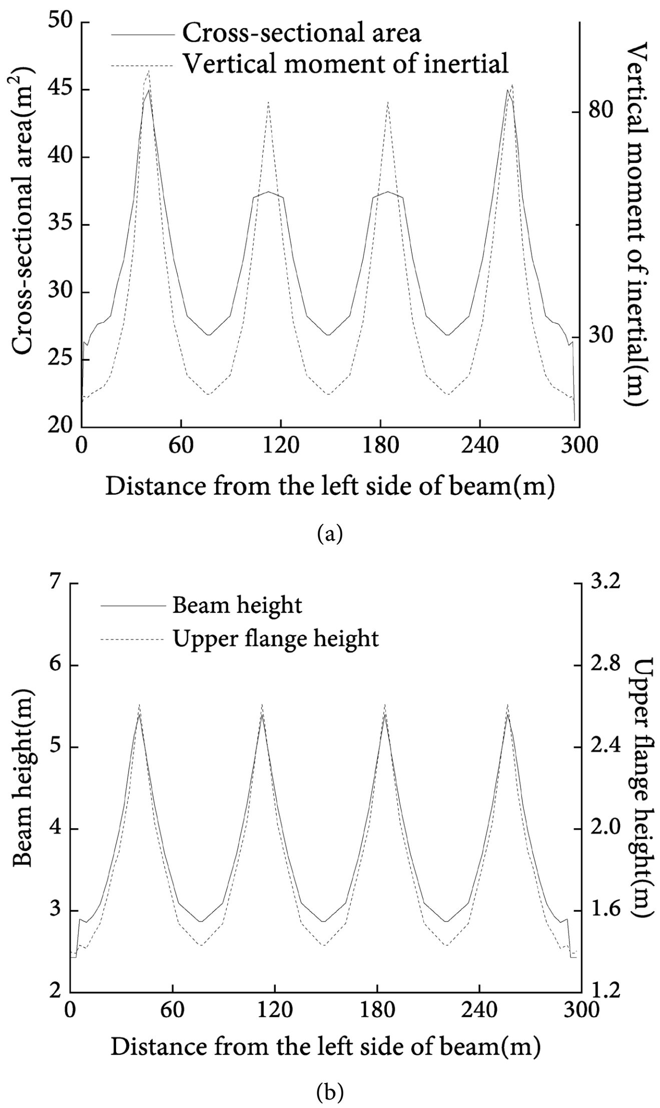
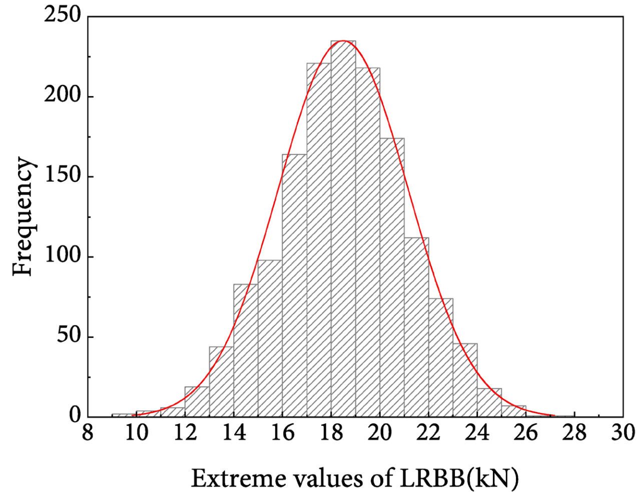


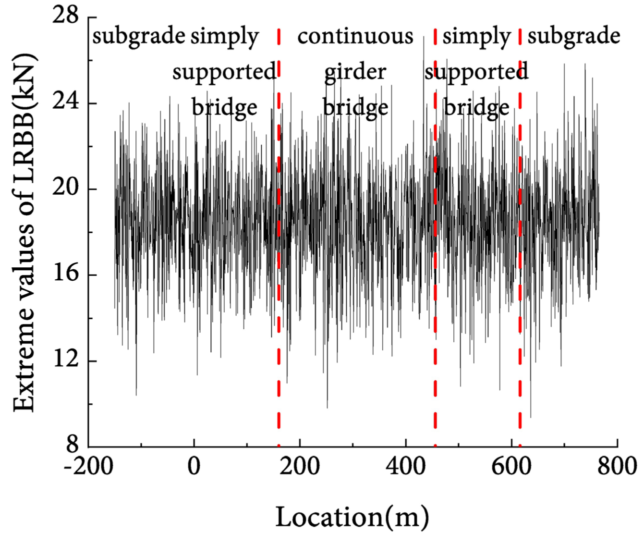
Figure 4. Cross-sectional parameters. (a) Cross-sectional area and vertical moment of inertial; (b) Beam height and upper flange height.

kN/cm. The longitudinal stiffness of the pier for the continuous beam with fixed bearing is 1500 kN/cm. The amplitude of the temperature variation of bridges is 15˚C.

The mass per unit length of rail is 75 kg. The cross-sectional area, vertical moment of inertial, Young's modulus and Poisson's ratio of rail are 95.04 cm^2, 4489 cm^4, 2.06 × 1011 N/m^2 and 0.3, respectively. The cross-sectional area and vertical moment of inertial of sleepers are 678 cm^2 and 32352.8 cm^4. Both the longitudinal resistance of fasteners and the LRBB are simplified to ideal elastic-plastic models as referenced in [26]. The ultimate resistance of fastener is 16 kN. The yield displacement of fasteners and LRBB is 2 mm. The LRBB corresponding to each sleeper are assumed mutually independent. The simulation model consists of 1529 sleepers, and the distribution of generated LRBB along the CWR is presented in **Figure 5**.



(a)



(b)

Figure 5. Distribution of generated LRBB along the CWR. (a) LRBB frequency statistics; (b) Distribution of LRBB.

According to the code [28], ZH load should be adopted for the heavy-haul railway. When the load is 250kN, the load coefficient is 1.1.

4. Calculation Conditions

Due to the randomness of LRBB, 2000 samples containing random LRBB are generated under each calculation conditions.

4.1. Expansion Condition

Figure 6 illustrates the distribution of rail expansion force under different conditions. The random means the results of one of the 2000 samples. The uniform denotes the results of condition with the same LRBB of 18.43 kN, which is the mean value of LRBB.

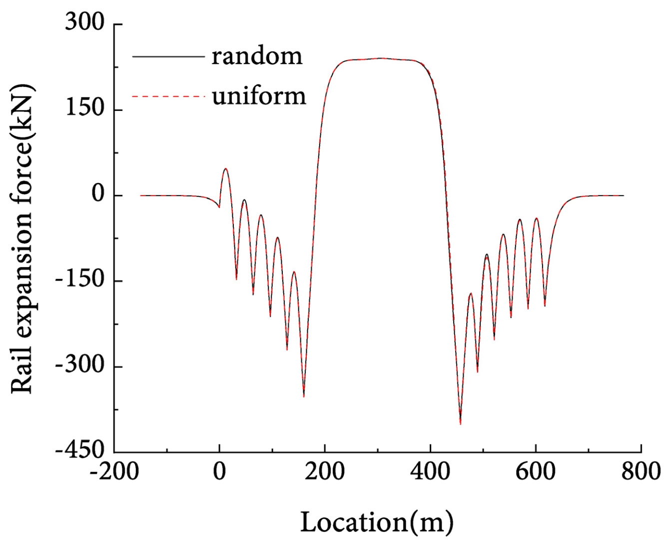


Figure 6. Comparison of rail expansion force.

The demonstrated results in Figure 6 reveal that the randomness of LRBB has little effect on the distribution law of rail expansion force due to change of LRBB under the random and uniform conditions, the amplitude of the rail expansion force changes slightly. The amplitudes of the rail expansion force under the two conditions are 396.66 kN and 403.98 kN, respectively. The difference is only 7.32 kN, which is less than 2.0% of the amplitude of rail expansion force under the uniform condition.

Figure 7 shows the amplitude distribution of rail expansion force with the results of 2000 samples. From the results, it can be seen that the amplitude of rail expansion force follows normal distribution, and its mean value is 403.91 kN, which is only 0.07 kN different from that of 403.98 kN under unique condition. It also means that the amplitude of rail expansion force under unique condition only has a guarantee rate of 50%. However, due to the small standard deviation, the amplitude of rail expansion force is only 407.31 kN with a guarantee rate of 95%, and it is only larger than that under unique condition by 3.34 kN. It is thus clear that the randomness of LRBB has little effect on track-bridge interaction under expansion condition.

4.2. Bending Condition

When the train load is located at the left-two spans of the continuous beam bridge, the rail bending force under different conditions is shown in Figure 8. Figure 9 shows the distribution of amplitude of rail bending compression force with 2000 samples.

It can be seen from Figure 8 that the randomness of LRBB also has little effect on the distribution law of rail bending force.

As shown in Figure 9, it can be seen that the amplitude of rail bending force considering the randomness of LRBB also follows a normal distribution. And the mean and standard deviation are 78.85 kN and 0.55 kN, respectively. The mean

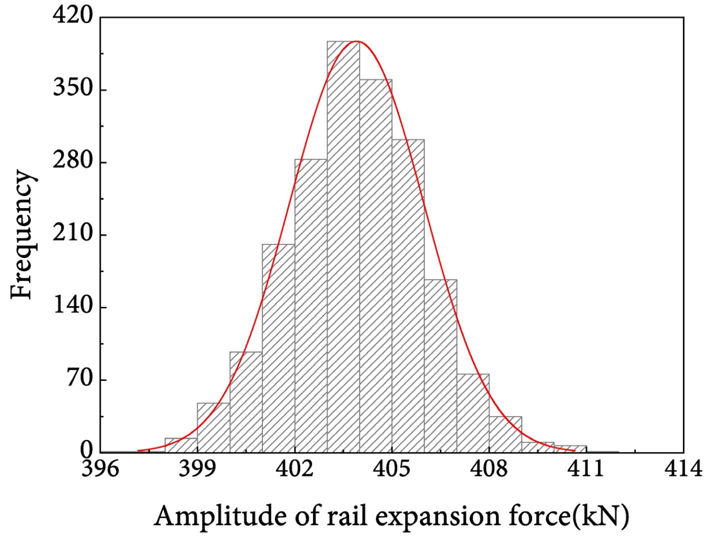


Figure 7. Distribution of amplitude of rail expansion force.

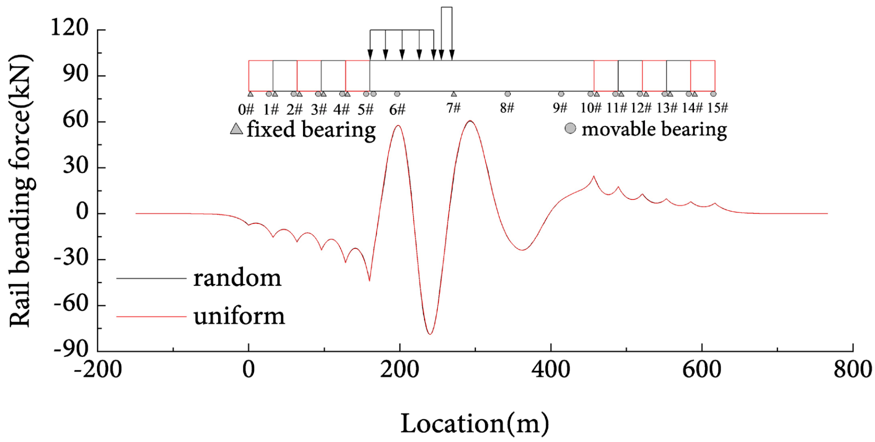


Figure 8. Comparison of rail bending force.

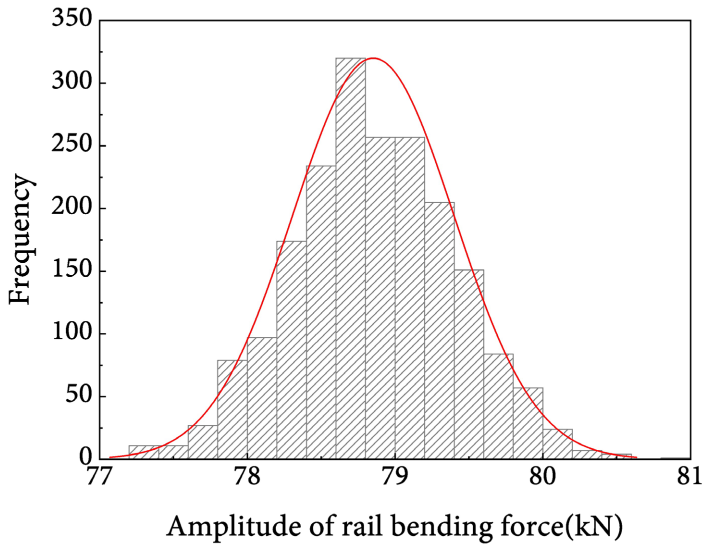


Figure 9. Distribution of amplitude of rail bending force.

value of the amplitude of rail bending force is approximately equal to that in Figure 8 under unique condition, with a difference of only 0.02 kN. Contrasting to the expansion condition, the standard deviation of rail bending force is smaller than that of rail expansion force, which indicates that rail bending force is less affected by LRBB than rail expansion force.

4.3. Braking Condition

When the length of train load is 400 m and one end of the load is located at the position of #10 pier, the rail braking force under different conditions is shown in Figure 10.

It can be seen from Figure 10 that the randomness of LRBB also has little effect on the distribution law of rail braking force. The amplitudes of braking force changes due to the change of LRBB. The amplitudes of rail braking compression force of random and uniform conditions are 689.51 kN and 683.75 kN. The difference is only 5.76 kN, less than 1% of the amplitude of uniform condition.

Figure 11 shows the distribution of amplitudes of rail braking compression force with 2000 samples.

From Figure 11, it can be seen that the amplitude of rail braking compression force under the influence of the randomness of LRBB follows normal distribution. The mean and standard deviation are 683.82 kN and 1.51 kN, respectively. The mean value is approximately equal to the amplitude of rail braking compression force under unique condition in Figure 10, and the difference is only 0.07 kN. The standard deviation is also small. That means the randomness of LRBB has little influence on the track-bridge interaction under braking condition.

4.4. Rail Breaking Condition

According to the results displayed above, the amplitude of rail expansion force under random and unique conditions occurs at the #10 pier, the location of the rail breaking is set the position. The longitudinal displacement of the broken rail is shown in Figure 12(a). Figure 12(b) shows the distribution of rail broken gap with 2000 samples.

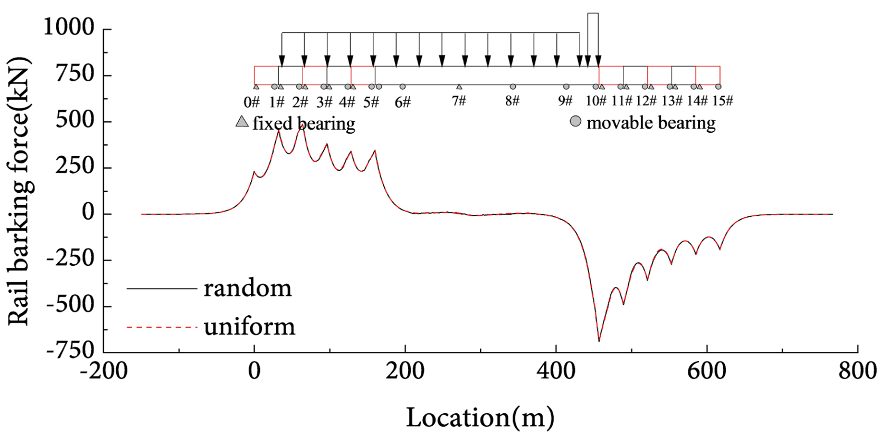


Figure 10. Comparison of rail braking force.

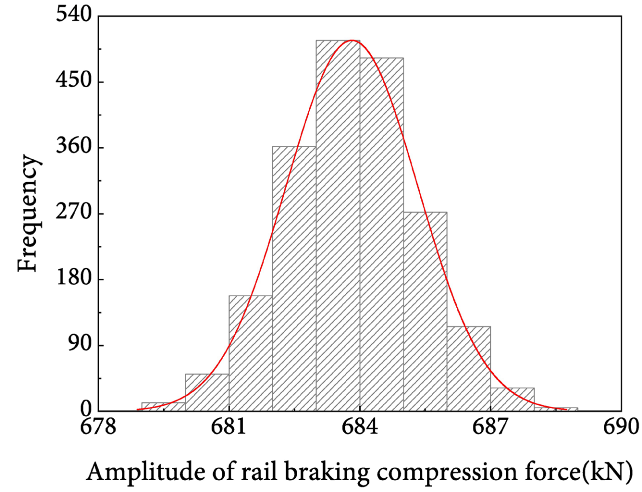
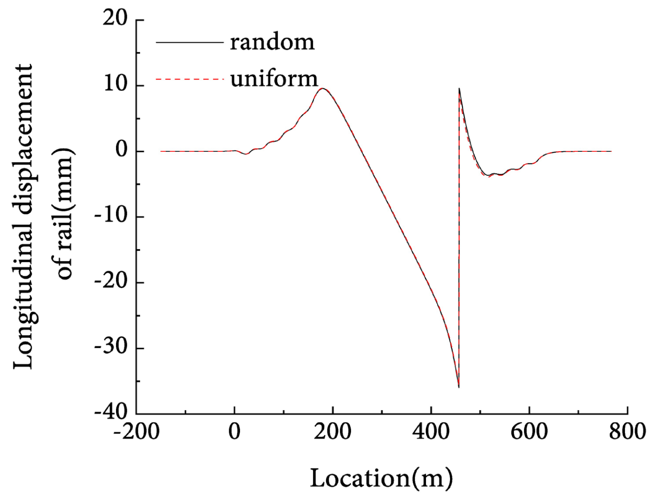
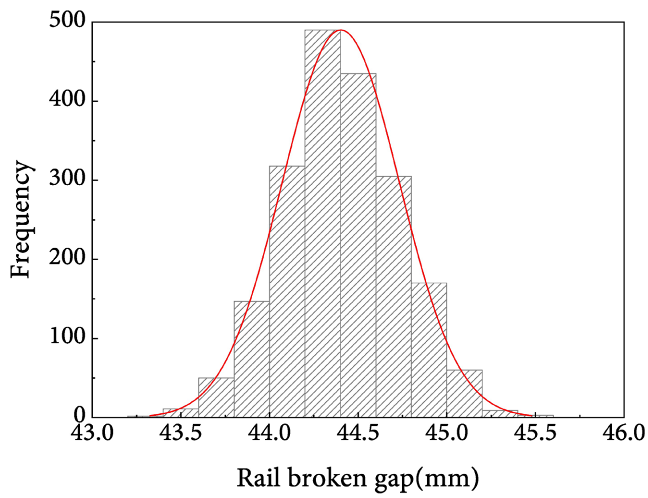


Figure 11. Distribution of amplitude of rail braking compression force.



(a)



(b)

Figure 12. Results of rail breaking condition. (a) Longitudinal displacement of rail; (b) Distribution of rail broken gap.

It can be seen from **Figure 12** that the rail broken gap with 2000 samples follows normal distribution, and the mean and standard deviation are 44.40 mm and 0.33 mm, respectively. The rail broken gap under unique condition in **Figure 12(a)** is 44.39 mm, which is only 0.01 mm different from the mean value shown in **Figure 12(b)**. It can be seen that the randomness of LRBB does not significantly affect the rail broken gap.

5. Conclusions

1) The distribution of LRBB corresponding to sleeper displacement of 2 mm is examined with the Shapiro-Wilk test, and it follows a normal distribution.

2) When the randomness of LRBB is considered, the amplitude of rail expansion force, rail bending force, rail braking force and rail broken gap all follow normal distributions. And the mean values are approximately equal to the results without considering the randomness of LRBB.

3) Although the randomness of LRBB has little effect on track-bridge interaction from the standard deviation of amplitude of the rail expansion force, the results can help to design CWR on bridge with limit state method.

4) The data of LRBB is directed towards specific railway track, so further experiments to test the LRBB of different railway tracks should be conducted to improve the parameters of LRBB.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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