New Rail Replacement Period Reflecting Results of Bending Fatigue Tests in High-cycle Region

Mitsuru HOSODA        Jun MIZUTANI        Ryuichi YAMAMOTO
Rail Maintenance and Welding Laboratory, Track Technology Division

To estimate the service life of rails, it is necessary to clarify the relationship between the stress and the number of loading cycles needed to reach breaking point through bending fatigue tests. In the previous studies, bending fatigue tests were conducted under high stress levels exceeding the stress generated on real tracks. In this study, bending fatigue tests were carried out under lower stress level conditions, and the service life of rails was estimated reflecting the results obtained in high cycle regions. Based on the results of these tests, this paper suggests it may be possible to extend the period between rail replacements.

**Keywords:** rail, bending fatigue test, high cycle region, period of rail replacement

1. Introduction

Rails are key track elements and ensure the safe running of trains. Maintenance management is therefore essential to prevent rail failure. One rail management method is to replace rails regularly before they reach the end of their service life. The factors for rail replacement include wear in curved sections, rail damage due to lateral cracks in the head and corrosion at the bottom and accumulated passing tonnage. Railway operators propose and apply intervals between rail replacements, taking into account life extension by rail grinding [1]. However, rail replacement is costly, and there is therefore demanded to extend the interval between rail replacements, to reduce maintenance costs.

The fatigue life of rails has been estimated from the relationship between stress generated by the rails and the number of loading cycles needed before to rupture, through bending fatigue tests. Figure 1 shows the results of bending fatigue tests of old rails including welded parts of rails in the previous study [1] and the S-N curves estimated from the results. The S-N curve is a curve showing the number of cycles that can be applied before rupture, when a certain cyclic stress is applied. The previous study [1] found:

1) There was no difference between the welded part and the base rail for fatigue strength, because the fatigue strength of the aged rail was affected by unevenness in the rail surface due to rust.
2) Fatigue strength after 2 million cycles of loading (hereinafter referred to 2 million cycles time-strength) was about 220 to 240 N/mm² in total stress amplitude.

However, actual rails were used for the stress region below 2 million cycles time-strength, and there is little knowledge concerning fatigue phenomena in this stress region. As a result, the authors decided that tests should be conducted under stress conditions that were closer to actual track conditions, to estimate the fatigue life with higher accuracy.

Therefore, in this study, bending fatigue tests of aged rails in the low stress region were conducted to obtain basic data, and the possibility of extending the period of rail replacement was examined.

2. Bending fatigue tests for aged rails [2]

Bending fatigue tests on actual rails would take a very long time, due to the low frequency of bending cycles [2]. Therefore, we conducted bending fatigue tests at a high frequency (about 20 to 25 Hz) on test specimens that would make it possible to obtain data efficiently in a shorter time. In general, it is reported that fatigue cracks originate on the surface of the material if breaking occurs in $10^7$ cycles or less, while the origin is located inside the material when breaking occurs in over $10^7$ cycles. However, it is known that the fatigue strength of rails with rusted surfaces is lower than that of new rails, due to the surface effect. Furthermore, in a corrosive environment, there were some cases in which rail breaking from corrosive holes on the rail surface occurred at several hundred million tons of accumulated tonnage [3].

From the above, in this study, the authors considered that cracking was likely to originate on the surface of the rail even when the number of loading cycles exceeded $10^7$. In the following tests, old JIS 60kg rails that had been in place for about 25 years and accumulated a tonnage of about 800 million tons were used.
2.1 Bending fatigue tests on actual rails

Figure 2 shows an actual rail set on a rail bending fatigue machine with a span of 1,300 mm. A four-point bending fatigue test was conducted using a one-sided swing mode in dry conditions. Six test rails were used, of which two had thermite welds and the other four were old and without welds. In order to prevent fretting fatigue at the loading point and around the support, rotatable rollers were set at each contact point. In addition, this machine was operated using load control. The stress generated at the rail bottom was converted using (1):

\[ F = \frac{4\pi Z}{L - L_1} \]  

(1)  

where \( F \): Load, \( \sigma \): Stress generated at the rail bottom, \( Z \): Section modulus, \( L \): Span, \( L_1 \): Loading point distance.

The minimum loading stress was 30 N/mm², and the test load was set so that the total stress amplitude was 160-210 N/mm²: a stress range which is lower than the 2 million cycles time-strength (220-240 N/mm²).

The test results are shown in Fig.3. As mentioned above, the fatigue strength of old rails is affected by unevenness of the rail surface due to rust. Therefore, on the premise that there is no difference between welded parts and the parent rails on fatigue strength [1], we plotted the data without distinguishing the welded parts and the parent rails.

Four of the six rails remained unbroken: three remained intact after 10 million cycles of loading, and one of them was still unbroken after a total stress amplitude of 180 N/mm² and 50 million cycles of loading.

2.2 Bending fatigue test on test specimens

The test specimens taken from rails were set on the test machine as shown in Fig.4. Bending fatigue tests were conducted using a one-sided swing mode in the base bottom tension condition. The frequency was 20-25 Hz. Although the bending fatigue tests were performed in dry conditions, an actual rail is exposed to wind and rain for several decades. In other words, the actual environment is different from test conditions. Therefore, in addition to the normal bending fatigue tests using the test specimens in dry conditions, bending fatigue tests were also conducted under wet conditions where water was dropped on the test specimen. 16 tests in dry conditions and 21 tests in wet conditions were performed. In the wet test, 0.5 mm³ of water was dropped into the shaded area in Fig. 5 once every 12 seconds.

Figure 6 shows the test results and the bending fatigue test results of the actual rail in Fig. 3. Two million cycles time-strength is about 360 N/mm² (total stress amplitude) under the dry condition. This strength is higher than that of the actual rail whose strength is from 220 to 240 N/mm². At total stress amplitude lower than 360 N/mm², the samples did not break after 50 million cycles of loading. On the other hand, under wet conditions, there were some cases in which samples broke at 2 million cycles of loading, between 270 to 340 N/mm² (total stress amplitude), and that broke at over 20 million cycles of loading in the vicinity of 250 N/mm² (total stress amplitude). For cycles of loading under 2 million, the results were similar to those under dry conditions.
2.3 Considerations for bending fatigue tests

Comparing the test results under the different conditions, we found the following features:

(1) Results from the tests using test specimens were almost the same in both dry and wet conditions when number of loading cycles was less than 2 million.

(2) In the bending fatigue tests on test specimens in dry conditions, test pieces did not break at over 2 million cycles of loading when total stress amplitude was under 360 N/mm². In wet conditions, however some test pieces broke at more than 2 million cycles when the total stress amplitude was equal to or under 340 N/mm².

(3) The time-strength of the actual rail was about 70% of the test specimen.

These results lead to the following considerations:

From the results of bending fatigue tests on test specimens in both dry and wet conditions, the influence of the wet conditions do not appear because the loading time for less than 2 million cycles, is short (about 22 hours).

Actual rails are exposed to wind and rain for a long time, but it is difficult to reproduce this environment exactly in a test. However, the wet condition test was more representative of a real situation than the dry condition test, because the wet condition test is a kind of corrosion fatigue test.

The difference in the test results between the test specimens and the actual rails is attributed to the difference in the effective stress gradient around the corrosion hole due to the size effect [4]. Taking account of this reasoning for the test specimens of the test results, we consider 70% of the total stress amplitude the time strength of the actual rail.

Figure 7 plots the data which are reduced to 70% of the fatigue test results of the samples test pieces. In this study, we focused on the fatigue life of the rail in the high cycle region. Therefore, a S-N curve is estimated by using the least-squares method intended for the S-N curve in the range of 2 million cycles time strength or less (red line in Fig. 7). Comparing the S-N curve of the aged rail laid on the conventional line estimated in the previous study (breakage probability 50%) [1] with the S-N curve obtained from this study (broken line in Fig. 7), we found that the S-N curve estimated from this study is slightly higher than that from the past test in the range of 2 million cycles time strength or less. This result suggests the possibility of extending the current replacement period based on the accumulated tonnage of rails.

3. Estimation for fatigue life of rails

The results given in the previous chapter confirm the possibility of extending the replacement cycle. Therefore, the fatigue life of the rail was evaluated using the life evaluation method [1] based on the accumulated damage law established in the past. Figure 8 shows the flowchart for predicting lifespan. Here, it is assumed that the welded part of rails has irregularities that increase in proportion to the passing of trains. The S-N curves in Fig. 7 were used in this calculation.

The calculation conditions and various numerical values for fatigue life prediction were mainly based on the previous study [1]. The track response model shown in Fig. 9 in which the rails are supported at finite intervals was used in order to estimate the bending stress which occurs on the rail bottom when the train runs on the track. Train load, track structure, and unevenness of top surface are consid-
In this calculation, two types of vehicles were assumed, and the static wheel load was set to 79 kN for the electric locomotive and 59 kN for the AC/DC limited express train, respectively. The train speed was set to 100 km/h for electric locomotive and 130 km/h for AC/DC limited express train. The bending stress corresponding to the unevenness of the welded parts was calculated by using the estimation formula for bending stress of the welded parts shown in Table 1.

The track conditions were assumed to be a ballast track and a floating sleeper of 1 mm. In addition, it was assumed that the local unevenness on the top surface of the welded parts would increase with accumulated passing tonnage. Based on the results of past measurements, the progress in unevenness was set to 0.1 mm/100 million tons for enclosed arc welds, and 0.05 mm/100 million tons for the other welds [1]. In addition, the estimations were carried out with or without rail grinding. It was assumed that the amount of grinding was set to 0.08 mm/100 million tons in case of rail grinding.

The failure probability has to be determined on calculating of the rail life, and it was set to 0.1% as in the previous study that estimated the rail life of the conventional lines [1]. The S-N curve estimated in the previous chapter has a 50% failure probability, and it is necessary to use this data to calculate the S-N curve of 0.1% failure probability. There are two calculation modes: one mode sets the standard deviation to constant, and the other mode sets the variation coefficient to constant, but the previous study found that the mode in which the standard deviation is a constant was evaluated on the safe side [5]. Therefore, based on the 50% failure probability S-N curve obtained in this study, the S-N curve of the 0.1% failure probability was calculated for when the standard deviation is constant.

Table 2 shows the results of estimating the fatigue life of rails by means of the S-N curve obtained in this study when rail grinding is not used. In addition, Fig.10 shows a comparison of the estimated results of the fatigue life due to the difference between the present study and the previous study. Under the calculation conditions of this study, there was little difference in the fatigue life due to train type. The estimated service life of the enclosed arc weld with significant progress in unevenness is about 700 million tons for the 50 kgN rail and about 1 billion tons for the 60 kg rail. These values exceed the current rail replacement cycle of conventional lines: 600 million tons for 50 kgN rail, 800 million tons for 60 kg rail. Furthermore, the estimated service life based on the S-N curve obtained in this study exceeds about 10% for the 50kgN rail, and about 30% for the 60kg rail than those based on the S-N curve obtained in previous studies.

Table 3 shows the estimated results of the fatigue life based on the S-N curve obtained in this study when rail grinding is used. In addition, Fig. 11 shows a comparison of the estimated results of fatigue life with and without rail grinding. When rails are ground regularly, the estimated service life of the enclosed arc weld is about one billion tons for the 50kgN rail and 1.5 billion tons for the 60kg rail. From this viewpoint we consider that there is a possibility of extending the period of rail replacement by means of...
Consequently, these results, under the calculation conditions of this study, suggest that the interval between rail replacements, based on accumulated tonnage, could be extended. However, when carrying out stricter examinations, fatigue tests of real rails need to be carried out on rails which are laid in target sections, and fatigue life predictions made using rail bending stress estimation formula based on the real vehicle and track conditions.

Also, in this calculation, the amount of unevenness progress of the enclosed arc weld was set to 0.1 mm/100 million tons based on the measurement results obtained in previous study. However, it is possible that the amount of unevenness progress of the current enclosed arc weld can be reduced, since the hard facing metal is applied to the top surface from the viewpoint of improving wear resistance. Therefore, it should be possible to further extend the replacement period by reexamining the data on how unevenness progresses in enclosed arc welds.

### 4. Conclusions

In this study, we conducted high-cycle fatigue tests in the stress region below 2 million time-strength, which is a region for which data is insufficient, and examined the possibility of extending the time between rail replacements. The results are summarized below.

1. Comparing the results of the bending fatigue tests on actual rails with those on test specimens, we found that the time-strength of actual rails is about 70% of that of the specimens. It is suggested that the reason for this is a difference in the effective stress gradient around the corrosion holes due to the size effect.

2. In the bending fatigue tests on test specimens in dry conditions, none broke at over 2 million cycles of loading when the total stress amplitude was less than $360 \text{ N/mm}^2$, but test pieces broke at over 2 million cycles of loading when the total stress amplitude was $340 \text{ N/mm}^2$ or less, in wet conditions.

3. The result of estimating the fatigue life by updating the S-N curve using the bending fatigue test results in the high cycle region of more than 2 million cycles time-strength shows that the estimated fatigue life tended to exceed that found in previous studies. Therefore, authors suggest it may be possible to extend the period between rail replacements.

4. In order to carry out stricter examinations, it would be necessary to conduct fatigue tests on real rails laid in target sections, and to predict the fatigue life using the rail bending stress estimation formula based on real vehicle and track conditions.

### References

[1] Deshimaru, T., Kataoka, H., and Abe, N., “Estimation of service life of aged continuous welded rail,” Quarterly Report of RTRI, Vol. 47, No. 4, pp. 211–215, 2006.

[2] Mizutani, J., Hosoda, M., Kataoka, H., and Yamamoto,
R., “Study on The Extension for Replacement Period of Rail Taking into Account The Fatigue Life of Rail on The Region of The High Cyclic Number,” Journal of railway engineering, Vol. 22, pp.173-177, 2018 (in Japanese).

[3] Nakamura, T., “Fundamental Knowledge of Metal Fatigue,” Journal of Japan Foundry Engineering Society, Vol. 79, No. 2, pp. 58-69, 2007 (in Japanese).

[4] Japan Society of Mechanical Engineers, Metallic Material, The design of Fatigue Strength (2nd Edition), 2003 (in Japanese).

[5] Kataoka, H., Abe, N., Wakatsuki, O., and Ishida, M., “Fatigue Strength of Rails,” The journal of Japan Railway Civil Engineering Association, Vol. 42, No. 4, pp.28-31, 2004 (in Japanese).

Authors

Mitsuru HOSODA
Assistant Senior Researcher, Rail Maintenance and Welding Laboratory, Track Technology Division
Research Areas: Civil Engineering

Jun MIZUTANI
Researcher, Rail Maintenance and Welding Laboratory, Track Technology Division
Research Area: Mechanical Engineering

Ryuichi YAMAMOTO, Dr. Eng.
Senior Chief Researcher, Head of Rail Maintenance and Welding Laboratory, Track Technology Division
Research Area: Rail Welding