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EXTENSION OF RAIL REPLACEMENT CYCLE USING RAIL HEALTH INDEX REFLECTED ONBOARD TRAIN DATA

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Abstract

To improve rail maintenance efficiency and enable rational extension of rail replacement intervals, this study investigates the bending fatigue behavior of aged rails and proposes a quantitative rail health evaluation method based on in-service condition data. Bending-fatigue tests were conducted on actual rails removed from commercial lines, with cumulative gross tonnage histories ranging from approximately 600 to 920 million tons. The test specimens included welded joints and intermediate rails with varying degrees of head-surface irregularities and hanging sleepers, both of which are known to increase bending stress at the rail foot. Fatigue tests focused on the high cycle region to clarify fatigue characteristics near and below the conventional fatigue limit. Track inspection data were used to estimate head-surface irregularities and the quantity of hanging sleepers, and these estimates were incorporated into numerical analyses to calculate rail-foot bending stress under actual service conditions. The results confirm that aged rails retain sufficient fatigue strength even at high cumulative tonnage levels, and that fatigue fracture is unlikely when the stress amplitude remains below approximately 180–200 MPa. Based on these findings, a rail-health index was defined using the ratio of applied bending stress to the fatigue limit, allowing quantitative assessment of fatigue risk. The proposed method enables identification of locations where fatigue damage may occur before conventional replacement intervals are reached and supports maintenance strategies that move beyond replacement based solely on cumulative gross tonnage. Integration of the rail health index into track maintenance database systems further enables practical visualization and condition-based decision-making for rail management.

Keywords: rail, track, fatigue life, health index, head-surface irregularities, hanging sleeper

1 Introduction

As part of rail maintenance and management, railway operators periodically replace rails before they reach their bending-fatigue life to prevent fatigue fractures. The replacement interval is determined based on the cumulative gross tonnage (axle load × number of axle passes) borne by the rail [1]. Research on the fatigue life of in-service rails has been conducted through fatigue testing and numerical analysis [2]. These studies indicate that the fatigue life of aged rails can be evaluated using two factors: the service history of the rail and the remaining fatigue life evaluated through fatigue testing. The former corresponds to the cumulative gross tonnage experienced during service. At the same time the latter is derived from the S–N curve obtained through fatigue tests conducted on rails removed from commercial tracks. Figure 1 shows the S–N curve for aged rails. The curve was obtained from tests on various welded joints, considered potential weak points due to head-surface irregularities, using rails with a service history of 540 million gross tons.

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The difference in fatigue strength among welding types was negligible regarding cracks initiated at the corroded surface of a rail foot. Furthermore, no significant difference was found compared with the fatigue strength of corroded rails that had been exposed for approximately five years but had no cumulative tonnage history [3].

Metal materials exhibit a fatigue limit, below which fatigue failure does not occur even under repeated loading [4]. For example, fatigue design guidelines for structures define a cut-off limit on the S–N curve, representing the stress level below which fatigue failure does not occur [5]. For aged rails, a stress amplitude of approximately 200 MPa is considered the fatigue limit, and fatigue failure is rarely observed below this level. Consequently, few fatigue test results exist for stress amplitudes below 200 MPa. In contrast, when no significant head-surface irregularities or hanging sleepers are present in commercial tracks, the bending stress at the rail foot is believed to fall well below the 200 MPa stress-amplitude range. Under such low-stress conditions, fatigue damage does not accumulate, and even if fatigue tests are conducted on aged rails with large cumulative tonnage histories, the results are expected to show little deviation from the S–N curve in figure 1. Therefore, in rail-life management, it may be feasible to introduce a cut-off limit and adopt a maintenance strategy in which periodic rail replacement is not performed if the rail is used under stresses below this limit.

In recent years, track inspection data have been increasingly used to estimate hanging sleeper conditions and railhead surface irregularities, both of which significantly influence bending stress at the rail foot [6]. These developments enable more accurate stress estimation in in-servise rails and improved fatigue life evaluation. While extensive research has been conducted worldwide on the fatigue life of railway components such as wheelset axles, comparatively limited attention has been paid to fatigue life assessment of rails themselves, despite their critical role in track safety [7, 8].

In this study, bending fatigue tests were carried out on aged rails to clarify fatigue characteristics in the highcycle region. Rail head surface irregularities and hanging-sleeper conditions were evaluated using track inspection data and incorporated into numerical analyses to calculate rail bending stress. Based on these results, a quantitative rail health evaluation method was proposed, enabling identification of locations where rail foot fatigue damage may occur before conventional replacement intervals and supporting condition-based maintenance.

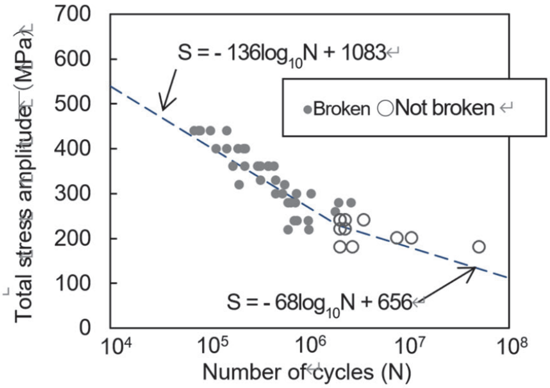
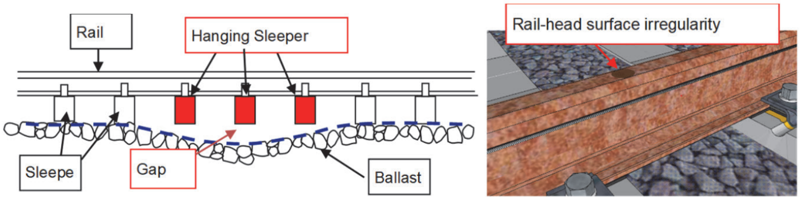


Figure 1 N curve on bending fatigue test of actual rails in the previous study [1]



(a) Hanging sleeper (b) Rail-head surface irregularity

Figure 2 Track irregularities affecting rail bending stress [2]

2 Fatigue testing of aged rails

Aged rails removed from commercial lines, with cumulative gross tonnage histories ranging from 600 to 920 million tons, were selected as test specimens. These included aged rails with welded joints as well as rails from intermediate sections with significant hanging sleepers. In the welded joints, head-surface irregularities reached up to 0.5 mm. Rails from intermediate sections exhibited a quantity of hanging sleepers of approximately 7 mm. A total of 45 specimens were tested: 20 gas-pressure welds, 5 thermite welds, 10 intermediate-section rails, and 10 expansion joints. Figure 3 outlines the rail bending fatigue testing machine and table 1 lists the test conditions. Each specimen was mounted on the machine, and fatigue tests were conducted under dry conditions using a four-point bending configuration with one-way loading. The rail was supported over a span of 1, 300 mm, and all loading and support points were equipped with rotatable rollers to prevent fretting fatigue (a fretting fatigue failure caused by microscopic relative slip between the specimen and the contact points of the machine).

Figure 4 shows the test results, and table 2 lists the intercepts of the S–N curves derived from the results. In the region above a stress amplitude of 200 MPa, all specimens fractured. The slope of the S–N curve was fixed at -136 for all conditions, and the intercept was determined using the least-squares method. The intercept values indicate that the S–N curve obtained in this study is nearly identical to those previously reported for aged rails with 540 million gross tons of service history and for new rails exposed for five years to develop a corroded surface. The intercepts also exceeded the lower-bound S–N curve (fracture probability 0.1%) proposed in earlier work to account for variability in fatigue strength of aged rails on conventional lines.

Furthermore, when the specimens were grouped into two categories – rails with cumulative tonnage ≤ 740 million tons (average 650 million tons) and ≥ 750 million tons (average 800 million tons) – the resulting intercepts were similar. These findings confirm that even rails with high cumulative tonnage histories, head-surface irregularities up to approximately 0.5 mm, or quantity of hanging sleeper up to approximately 7 mm retain sufficient fatigue strength for continued service. In the stress-amplitude range of 180–200 MPa, some specimens fractured while others did not, but all specimens remained unbroken at amplitudes below 180 MPa.

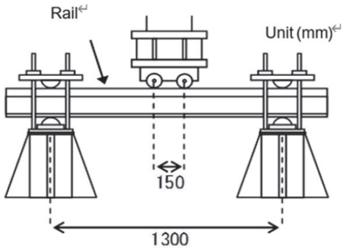


Figure 3 Overview of bending fatigue test of actual rail [1]

Table 1 Conditions for bending fatigue test of actual rail

Test method	Four-point bending test
Minimum stress (at rail bottom surface)	30 MPa
Frequency	1.0 ≈ 3.0 Hz

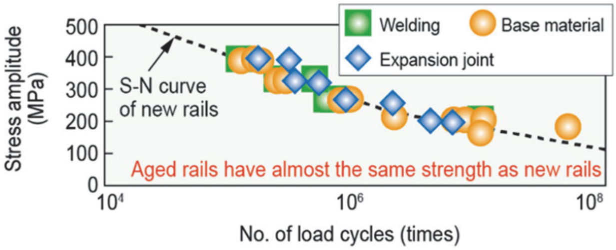


Figure 4 Results of bending fatigue tests on aged rails [9]

Table 2 Intercept of S-N curve obtained from test results (slope is constant value as -136)

Items	Intercept
All specimens in this test	1,085
Specimens for cumulative tonnage less than 740 MGT (average 650 MGT)	1,075
Specimens for cumulative tonnage more than 750 MGT (average 800 MGT)	1,098
Previous study (average 540 MGT)	1,083

3 Extension of replacement intervals and establishment of a method for quantitatively evaluating rail health

The rails tested in this study, which had accumulated up to 920 million gross tons, exhibited sufficiently high fatigue strength relative to the bending stresses generated at the rail foot under actual service conditions. As long as track maintenance ensures that the applied stress does not exceed 180 MPa, consistent with typical service conditions, fatigue accumulation is expected to remain negligible. It is reasonable to infer that even if cumulative gross tonnage exceeds 1 billion tons, the likelihood of fatigue fracture at the rail foot remains low. In structural fatigue design, a stress cut-off limit is generally defined when components are used under stress levels below a certain threshold, and fatigue accumulation need not be considered under such conditions [4]. Depending on the operator's strategy, if track conditions are well understood and maintained such that the stresses generated during train passage remain low, and if the rail surface remains stably corroded, a reduction in fatigue strength is unlikely. Under such circumstances, it may be reasonable to consider maintenance strategies that do not rely solely on periodic replacement based on cumulative gross tonnage.

To establish a cut-off limit for rail-foot bending stress below which periodic rail replacement is unnecessary, the fatigue limit of the rail material, defined as the stress level below which fatigue failure does not occur, is adopted, as is common practice in structural fatigue design. Rail health is quantitatively evaluated using a health index defined by the ratio of the fatigue limit to the applied bending stress, and maintenance management aims to maintain this index above a prescribed threshold. The rail-health index is defined as:

$$f_h = 1 - (\sigma_m/\sigma_c) \tag{1}$$

Where:
f_h - health index
σ_m - bending stress at the rail foot [MPa]
σ_c - fatigue limit [MPa].

Numerous experimental studies have investigated the fatigue strength of rails under long-term service conditions. These studies consistently show that rails in a new condition with a mill-scale surface exhibit fatigue strengths of approximately 320 MPa [3]. In contrast, rails that have been exposed to the open atmosphere for several years typically exhibit a reduced fatigue strength of around 200 MPa due to surface corrosion and environmental effects. Moreover, for rails installed in open environments – excluding persistently wet locations such as tunnels or level crossings – fatigue strength values close to 200 MPa have been widely reported even after long-term service [1-3]. Based on these accumulated experimental findings, a fatigue limit of 200 MPa was adopted in this study as a representative and conservative reference value. Although further investigation is required to fully quantify the effects of long-term microstructural evolution, previous material studies indicate that the stress level corresponding to the crack-initiation limit, immediately prior to fatigue failure, is approximately 10–20% lower than the fatigue limit [5]. Accordingly, even if the true fatigue limit were to decrease moderately due to long-term degradation, the proposed rail-health index would retain a sufficient safety margin. From this perspective, threshold values in the range of 0.2–0.3 were deliberately selected to ensure conservative fatigue-risk assessment and robustness against potential downward deviation of the fatigue limit.

Although the final stress estimation equation is expressed in a linear form, the rail stress data used to derive this equation were obtained from vehicle–track dynamic simulations that explicitly account for nonlinear and frequency-dependent behavior. In particular, the vehicle–track interaction was modeled using a dynamic response framework incorporating rail–wheel contact springs, sleeper-support nonlinearity represented by bilinear stiffness characteristics, and dynamic amplification effects arising from vehicle mass, suspension properties, and running speed. Consequently, the effects of rail-head surface irregularity and hanging-sleeper conditions on bending stress, including wheel-load fluctuation and resonance phenomena, are reflected in the simulated stress responses. The linear regression equation was subsequently derived as a practical representation of these simulation results for implementation in maintenance management systems.

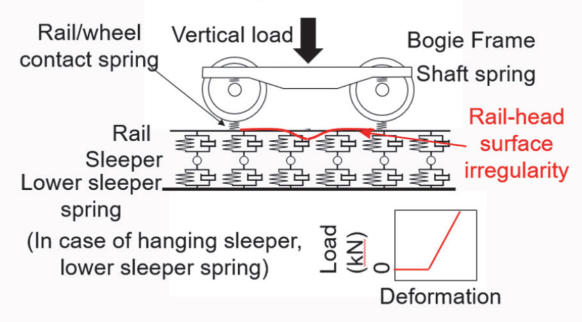


Figure 5 Analysis model for estimating rail bending stress

Table 3 Estimation formulas for rail bottom bending stress

Rail type	**Estimated formulation** [MPa]
50 kgN	$15.1\,V+6.3\,H+38.1$

4 Implementation of a rail-health evaluation method within track-maintenance database systems

To facilitate practical use of the rail-health evaluation method by railway operators, a system design was developed that enables the calculation and chart-based visualisation of rail health within widely used track-maintenance database systems (for example, LABOCS, which is commonly used in Japan [10]). The bending stress at the rail foot, is calculated using table 3, which expresses the relationship between head-surface irregularity, the quantity of hanging sleepers, and bending stress obtained from vehicle-running simulations. In this system, head-surface irregularity and quantity of hanging sleeper are estimated from axle-box acceleration and vertical-displacement data measured by track-inspection vehicles. The specific steps are:

- for each evaluation segment (for example, within ±3 m of the peak quantity of hanging sleeper location), the maximum quantity of hanging sleeper and the head-surface irregularity estimated from the maximum and minimum axle-box acceleration values are extracted and converted into waveform data
- using these waveforms, the bending stress at the rail foot is estimated, and the rail-health index is calculated.

A sample chart display of the rail-health index is shown in figure 6. The chart enables visual identification of locations where rail health deteriorates, and it also clarifies the relative influence of head-surface irregularity and quantity of hanging sleeper on the health index. This chart allows maintenance personnel to determine appropriate countermeasures based on the dominant degradation factors. In addition, field measurements of head-surface irregularity at hazardous locations can be omitted, improving maintenance efficiency.

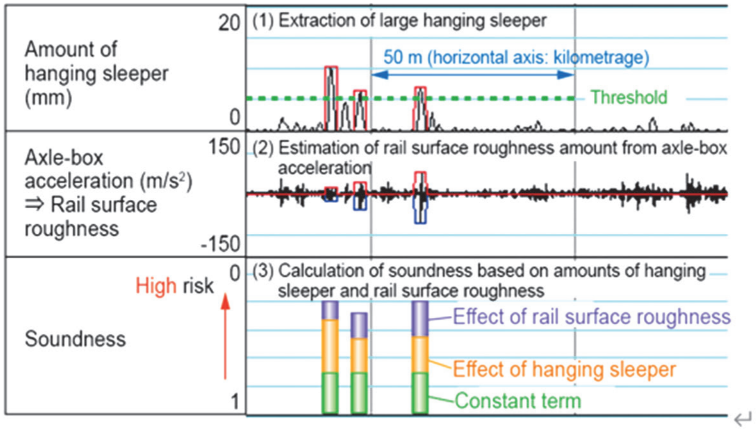


Figure 6 A sample chart display of the rail-health index [9]

5 Conclusion

This study examined the rail-replacement interval currently defined based on bending-fatigue considerations at the rail foot. Fatigue tests were conducted using actual-aged rails, and the potential for extending the replacement interval was evaluated. In addition, a rail-health evaluation method incorporating head-surface irregularity and quantity of hanging sleeper, both key factors influencing fatigue life, was proposed. Fatigue tests were performed on aged rails with cumulative gross tonnage histories of approximately 800 million tons, including specimens with a quantity of hanging sleeper up to 7 mm or head-surface irregularities up to 0.5 mm. For rails that had reached the current replacement interval, fatigue strength comparable to previously tested aged rails with 540 million tons of cumulative tonnage was confirmed. These results indicate that, provided the quantity of hanging sleepers and head-surface irregularity remain below certain thresholds, further extension of the replacement interval is feasible. Moreover, even when such irregularities are present, no fatigue fracture occurred when the stress amplitude remained below 200 MPa, suggesting that periodic replacement may be unnecessary under these stress conditions. To prevent rail breakage at locations with significant head-surface irregularity or quantity of hanging sleeper when replacement intervals are extended or eliminated, a rail-health index was proposed. This index is derived from the bending stress at the rail foot and the fatigue limit of the material. By maintaining the rail-health index above 0.3 through appropriate management of head-surface irregularity and quantity of hanging sleeper, fatigue fracture originating at the rail foot can be avoided. It should be noted that other forms of damage, such as corrosion or transverse head cracking, must be managed separately.

References

[1] Deshimaru, T., Kataoka, H., Abe, N., Ohno, T.: Method for fatigue life for used CWR, RTRI Report, 20 (2006) 4, pp. 5-10

[2] Hosoda, M., Mizutani, J., Iwasaki, M., Yamamoto, R.: Expectation method for fatigue limit of used rail on railway by surface roughness and effect of difference of various fatigue test methods, Transactions of the JSME, 86 (2020) 888, DOI: 10.1299/transjsme.20-00147

[3] Railway Technical Research Institute, Design Standards for Railway Structures and Commentary (Track Structure), pp. 33-39, 2011.

[4] Murakami, T.: Metal fatigue effects of small defects and nonmetallic inclusions, Yokendo, 2004.

[5] Japanese Society of Steel Construction, Fatigue design recommendations for steel structures, pp. 21-50, 2012.

[6] Kusuda, M., Tanaka, H., Kataoka, H.: Confirmation of the effect of track specifications on detecting unsupported sleepers and building a calculation method for practical work, Journal of structural engineering, 65A (2019), pp. 52-62

[7] Náhlík; L., Pokorný, P., Ševčík, M:, Fajkoš R., Matušek, P., Hutař, P.: Fatigue lifetime estimation of railway axles, Engineering Failure Analysis, 73 (2017) 3, pp. 139-157, DOI: 10.1016/j.engfailanal.2016.12.014

[8] Pokorný, P., Hutař, P., Náhlík, L.: Residual fatigue lifetime estimation of railway axles for various loading spectra, Theoretical and Applied Fracture Mechanics, 82 (2016) 4, pp. 25-32, DOI: 10.1016/j.tafmec.2015.06.007

[9] https://www.rtri.or.jp/eng/rd/seika/2024/02-12.html, 12.12.2025.

[10] Railway Technical Research Institute, Track maintenance management database system LABOCS, Railway Technical Research Institute(online), https://www.rtri.or.jp/rd/division/rd45/rd4530/rd45300102.html, 12.12.2025.