NIPPON STEEL TECHNICAL REPORT No. 133 MARCH 2025

Technical Report / Research

Railway Wheel Web Allowable Stress Diagram

Takanori KATO*
Taizo MAKINO
Chihiro KOZUKA
Miyuki YAMAMOTO
Yoshinari YAMAMURA

Abstract

JRIS J 0405 standard is the fatigue design method of the railway wheel web; however, this standard does not specify any evaluation method considering the thermal stress due to tread braking. Since thermal stress can be regarded as the average stress in the endurance limit diagram, it is necessary to evaluate the fatigue strength at a high stress ratio. In order to ensure safety, it is necessary to specify the allowable stress considering the variation of the fatigue properties and the mass-produced wheels. In this study, plane bending fatigue tests were conducted on cut wheel specimens, and the variation of various properties of mass-produced wheels was statistically evaluated. The fatigue limits obtained from the fatigue tests were accurately approximated by a curve combining the σ_a–σ_T ***diagram and the*** $\sigma_{max}=\sigma_f$ ***diagram. The equivalent standard deviation was obtained from the variation of each property, and the allowable stress diagram of the wheel web was determined so that the fracture probability was less than*** 10^{-6}.

1. Introduction

Railway wheels (hereinafter, “wheels”) are critical safety parts that must have sufficient durability and offer high safety. A wheel mainly consists of three parts: From the outside, a rim, web, and hub.[1] The rim has a flange and tread that comes into contact with a rail. For wheels that are used on conventional trains in Japan, a braking method in which the brake shoes are pressed to the treads is often used to reduce the speed. Because no direct force is applied to webs, the shape is designed such that the thickness becomes as thin as possible to reduce the weights of wheels. Because cyclic stress generated due to reaction force from a rail works on the web as the wheel rotates, fatigue limit design is applied.

In Japan, the Japan Association of Rolling Stock Industries provides web fatigue design standards (JRIS J 0405).[2] However, these standards do not consider the influence of tread braking in design stress calculation. Accordingly, in actual calculation, thermal stress due to tread braking is individually added based on experience and data that were acquired over many years so as to make evaluations. Whereas, thermal stress refers to stress that works on a web due to thermal expansion of the rim caused by heat input from tread braking. Thermal stress may sometimes become high tensile stress. As overseas wheel web design methods, European Norm (EN) 13979-1[3] is provided. This norm also does not consider the influence of tread braking in web fatigue design as is the case with the aforementioned JRIS J 0405.

In recent years, the rolling stock industry in Japan has been promoting globalization and Japanese rolling stock started adopting overseas wheels on a trial basis.[4] As described above, the overseas standards do not specify any web fatigue design methods that consider tread braking. Accordingly, it is difficult to objectively verify the appropriateness of the design of wheels under test. To resolve this problem, it is required to clarify and standardize objective fatigue design methods that appropriately consider thermal stress due to tread braking.

This report aims at proposing an appropriate allowable stress line, which is a requirement to achieve the aforementioned resolution. When tread braking is applied, on the web, thermal stress superimposes on the stress caused by reaction force from the rail.[5] Compared with the cyclic stress that occurs as a wheel rotates, thermal stress continues to be applied longer and its frequency is lower. Accordingly, evaluating thermal stress as mean stress is appropriate. Evaluations are made under conditions where the mean stress is high; in other words, the stress ratio is high. In addition, the statistical variability of fatigue strength data is not completely clear. For

---

* Dr. Eng., Chief Manager, Head of Dept., Railway, Automotive & Machinery Parts Research Dept., Kansai R & D Lab.
1-8 Fuso-Cho, Amagasaki City, Hyogo Pref. 660-0891

example, it is unknown which safety factor of a wheel web that is calculated using an existing fatigue design method corresponds to what level of fracture probability. Therefore, this paper focuses on two points: High stress ratio and statistical variability; we performed fatigue tests by changing the stress ratio to evaluate the statistical variability of the fatigue properties themselves. In addition, we investigated various properties of the webs of mass-produced wheels and converted the results into fatigue strength so as to evaluate the statistical variability of the fatigue properties of the mass-produced wheels. Based on such statistical variability, an allowable stress line where the fracture probability is less than 10^{-6} was proposed in a form that corresponded to an endurance limit diagram. This paper is a summary based on the paper prepared by the authors etc.[6)]

2. Wheel Web Fatigue Strength Evaluations

2.1 Tested wheels

Table 1 lists the chemical composition ranges of the tested wheels. **Table 2** lists the mechanical properties of the wheel web subjected to the fatigue test. The microstructure of the wheel web is pearlitic structure.

2.2 Test procedure and conditions

Fan-shaped pieces that were cut from actual wheels and for which the angle is 30 degrees were used as test specimens for fatigue tests. **Figure 1** shows the appearance of the test specimen. **Figure 2** schematically illustrates the plane bending fatigue test. As shown in the figure, a load equivalent to lateral load was applied in each test. During the test, the stress variation was measured with strain gauges attached at the root of the web on the hub side. The tests involving an electro-hydraulic servo fatigue tester were performed at ambient room temperature. The stress ratio R was set to −1, 0.1, 0.5, or 0.7 through load control. The test frequencies were 2 to 6 Hz. When the test piece had not broken when the number of cycles reached 10^7 cycles, the test was terminated.

2.3 Test results

Figure 3 shows the appearance of a broken test specimen. The specimen is broken near the section with the gauges attached and a fatigue crack initiating from the surface is seen.

Figure 4 shows the S–N data of the wheel webs that were organized using the amplitude of the maximum principal stress for each stress ratio R. This paper referred to the Japan Society of Mechanical Engineers' standards[7)] to obtain the P–S–N line. The fatigue limit when the fracture probability (P) was 50% was calculated as the mean of 1) and 2) below: 1) The minimum fracture stress value and 2) the maximum non-fracture stress value that is smaller than the

Table 1 Chemical composition ranges for the tested wheel[6)]

(mass%)

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V
Maximum	0.75	0.35	0.90	0.045	0.050	0.30	0.30	0.30	0.08	0.05
Minimum	0.60	0.15	0.50	-	-	-	-	-	-	-

Table 2 Example of mechanical properties of the tested wheel web[6)]

0.2% proof stress (MPa)	Ultimate tensile strength (MPa)	True fracture stress (MPa)	Elongation (%)	Reduction of area (%)
446	871	1 263	17.6	40.5

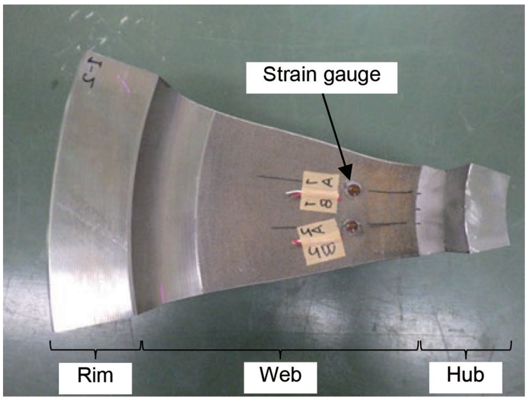

Fig. 1 Example of photo of cut wheel for fatigue test[6)]

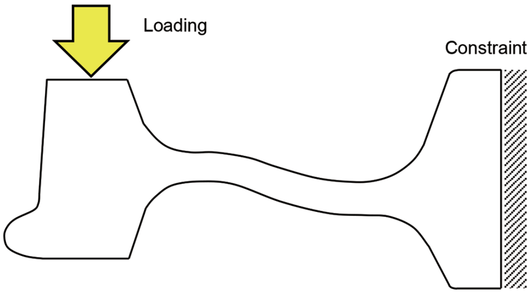

Fig. 2 Schematic illustration of plane bending fatigue test

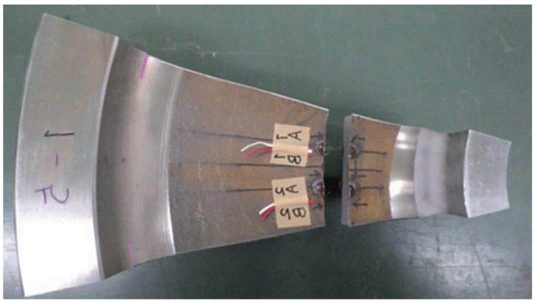

Fig. 3 Examples of photos of fractured cut wheel[6)]

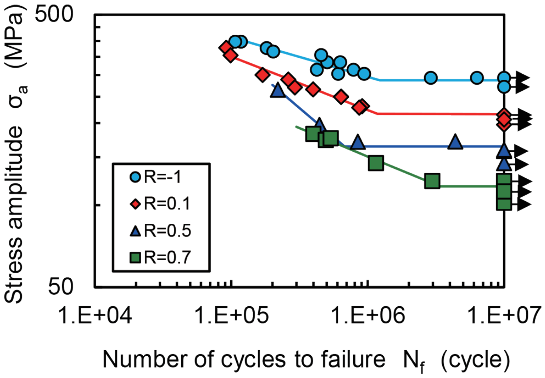

Fig. 4 S–N data obtained from fatigue tests fracture stress value 1). **Figure 5** is an endurance limit diagram with the fatigue limits where the *P* is 50% plotted. Whereas, the fatigue limits are expressed as the maximum principal stress. The graph shows that the fatigue limits for the stress ratios form an almost straight line.

3. How to Determine the Design Curve

Below is the basic concept to determine the design curve based on the fatigue test results that were obtained as described in the previous chapter.

- The fatigue limits obtained through the fatigue tests are approximated using a conventional diagram model that has been proposed as an endurance limit diagram.
- To ensure safety in actual service, allowable stress is calculated from the aforementioned fatigue limits so as to satisfy the necessary fracture probability.
- The fracture probability is determined considering statistical variability of the materials themselves, and that of mechanical properties and processing surface properties of mass-produced wheels.

First, to discuss a diagram model to be applied to the design curve, **Fig. 6** compares the fatigue limits obtained in the fatigue tests to an endurance limit diagram model. The σ_a–σ_T line (the solid line in the figure, σ_a: fatigue limit expressed by stress amplitude, σ_T: true fracture stress) is very close to the test result, which shows that the line is appropriate as a diagram model. However, the approximation accuracy at stress ratios larger than the test data range is not clear. The Fatigue Design Handbook[8)] shows that regarding many steel types, as the stress ratio *R* is higher, the fatigue limit tends to decrease toward the ultimate tensile strength σ_B. Accordingly, in this paper, while referring to the Fatigue Design Handbook, we determined to use the combination (the red line in the figure) of 1) and 2) below as the diagram model of the design curve: 1) σ_a–σ_T line and 2) straight line that connects σ_B and the point at which the maximum stress σ_{max} (sum of the stress amplitude and mean stress) during one cycle of stress variation on the σ_a–σ_T line is equal to flow stress σ_f (average of the yield strength and ultimate tensile strength).

Then, based on the diagram model above, an allowable stress line that considers fracture probability was created. Such line is described in detail below. **Figure 7** schematically illustrates the outline of an allowable stress line. The four types of characteristic values

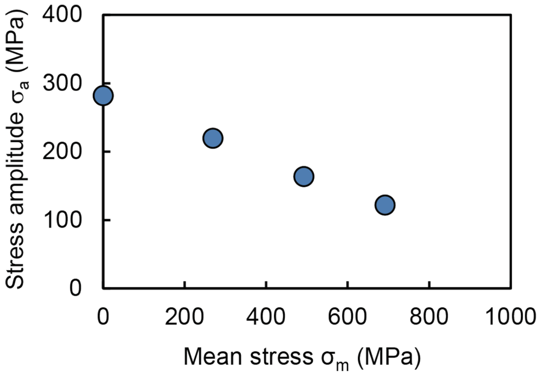

Fig. 5 Relationship between fatigue limits and mean stress of wheel web

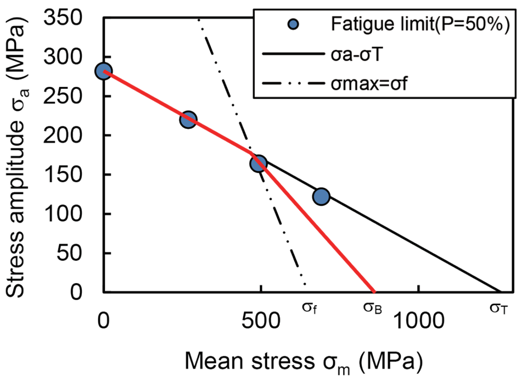

Fig. 6 Endurance limit diagrams of wheel web[6)]

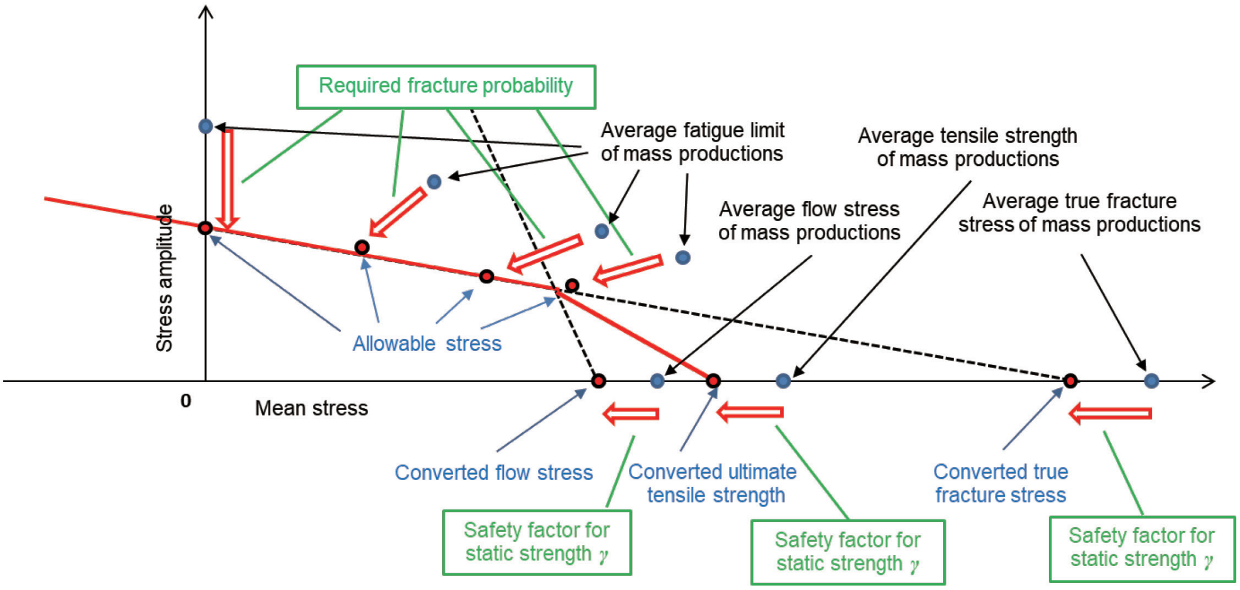

Fig. 7 Method of allowable stress lines of wheel web[6)]

listed below determine the allowable stress line.

(1) Allowable stress

Based on the fatigue test result for each stress ratio ($R = -1$, 0.1, 0.5, or 0.7), the fatigue limit that was calculated so as to satisfy the fracture probability is regarded as allowable stress.

(2) Converted true fracture stress value

With regard to the allowable stress for each stress ratio that was obtained in (1), a straight line is found by a least squares approximation and the intercept of the horizontal axis of the line is regarded as the converted true fracture stress value. The ratio of the obtained value to the average true fracture stress of the mass-produced wheel is regarded as the safety factor for static strength (γ).

(3) Converted flow stress value

The average flow stress of the mass-produced wheel and the safety factor for static strength that was obtained in (2) are used to calculate the converted flow stress value.

(4) Converted ultimate tensile strength value

As is the case with the flow stress in (3), the converted ultimate tensile strength value is calculated.

4. Allowable Stress Line Evaluation Results

This chapter describes the results of the allowable stress line examination that was conducted according to the procedure described in the previous chapter.

4.1 Statistical investigations of static strength

Among the characteristic values mentioned in the previous chapter, those related to static strength ((2) to (4) in the previous chapter) are determined by finding the statistical variability of the strength of mass-produced wheels. A test specimen was sampled from the webs of mass-produced wheels and they were subjected to a tensile test to evaluate the statistical variability. The targets are 15 wheels from three different lots. **Figure 8** exemplifies the frequency of the ultimate tensile strength that was obtained in the tensile tests. These results were used to find the maximum, minimum, and mean stress and standard deviation for each characteristic.

4.2 Statistical evaluations of the factors that affect fatigue limits

The allowable stress ((1) in the previous chapter) is calculated considering the statistical variability of the fatigue properties themselves and that of the mass-produced wheels. The specific procedure is as follows: 1) The standard deviation is found from the statistical data on each characteristic, 2) the standard deviation is multiplied by the factor, 3) the obtained value is subtracted from the average fatigue limit (equivalent to 50% of the fracture probability) that was obtained in the fatigue test, and 4) the calculated value is converted into allowable stress that corresponds to the supposed fracture probability. For example, if a value that is double the standard deviation is subtracted, the fracture probability is 2.3% and if triple, the fracture probability is 0.1%.

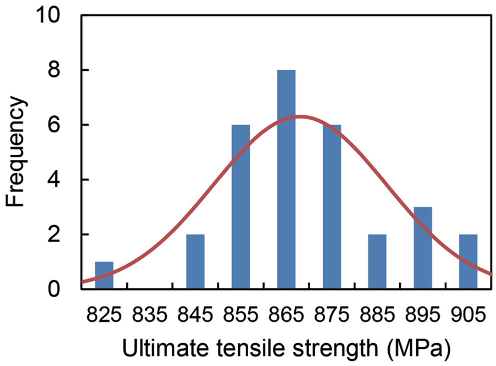

Fig. 8 Frequency of ultimate tensile strength of wheel web in mass productions

The statistical variability of the fatigue properties can be found from the fatigue test results described in Chapter 2. Meanwhile, the statistical variability of mass-produced wheels can be evaluated by the fatigue tests of many mass-produced wheels. However, such tests take too long and thereby it is practically impossible. Consequently, the statistical variability of mass-produced wheels was evaluated by calculating the statistical variability of each factor that would affect fatigue limits and then by converting the results into fatigue limits. The influential factors are as follows: (1) Static strength that was calculated in the previous section, (2) residual stress, and (3) surface roughness. Although this paper omits the details, the data on the characteristics was obtained through various measurements targeting the wheels that were subjected to the static strength investigations in the previous section.[6]

As described above, the four different standard deviations are obtained: Fatigue properties themselves, and items (1) to (3) above. These four should be combined to obtain one standard deviation. As the method, the root sum square of each type of standard deviation was used for calculation.[9] The combined standard deviation that was obtained according to the aforementioned procedure is 0.0230 when the stress ratio is −1. It is 0.0200 when the stress ratio is 0.1, 0.0181 when the stress ratio is 0.5, and 0.0165 when the stress ratio is 0.7. Using these values enables calculation of the allowable stress at each stress ratio for any fracture probability.

4.3 Proposal of an allowable stress line

The fracture probability required to determine the allowable stress was determined as follows. Given that the quantity of wheels manufactured in Japan per year was approximately 100 000 and the service life was approximately 10 years, the fracture probability is 1/(100 000 pieces × 10 years) = 10^{-6}. **Figure 9** is the allowable stress line that was obtained according to the concept shown in Chapter 3 by a least squares approximation of the fatigue strength with the fracture probability of 10^{-6}, i.e., allowable stress. The formulas below express the obtained line.

$$\sigma_{al} = -0.202\,\sigma_m + 220 \quad (\text{stress ratio } R \leq 0.51) \tag{1}$$

$$\sigma_{al} = -0.426\,\sigma_m + 313 \quad (\text{stress ratio } R > 0.51) \tag{2}$$

Where, σ_{al} is the allowable stress (MPa) expressed with stress amplitude and σ_m is the mean stress (MPa).

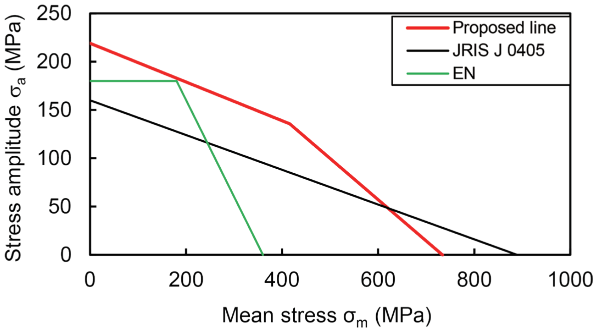

Fig. 9 Proposed allowable stress line for wheel web and other existing design curves[6]

The red line in the figure is the allowable stress line. The figure also shows the allowable stress line (black solid line) of the existing standards (JRIS J 0405) and that (green line) of the EN standards for comparison. The graph shows that the line of the existing JRIS standards is located on the safety side in excess and the EN standards' line does not assume it will be used when the stress ratio is high and thereby it cannot be used to evaluate the safety when tread braking is applied. Using the allowable stress line proposed in this paper makes it possible to rationally undertake fatigue strength design for wheel webs when a relatively high load of tread braking works on them while securing sufficient safety. For example, using the allowable stress line proposed in this paper enables considering the shape of lightweight wheels while securing safety against high-load tread braking.

5. Conclusions

To establish a wheel web fatigue design method when tread braking is applied to railway wheels, in particular, we performed fatigue tests and investigated the characteristics of mass-produced wheels. Based on the results, an allowable stress line was considered. The fatigue test results show that the higher the stress ratio, the lower the fatigue limit. The fatigue limit was in nearly linear relation with the mean stress.

An allowable stress line that considered the statistical variability of fatigue strength and that of mass-produced wheels was discussed. The statistical data on the various factors that would affect fatigue limits were converted into statistical data on fatigue limits and then the standard deviation was calculated. The obtained standard deviation was for each factor and thereby the root sum square for each factor was used to combine the deviation values so as to obtain the combined standard deviation.

The fatigue strength for which the fracture probability was less than 10^{-6} was selected as allowable stress and an allowable stress line was found so as to satisfy the value at each stress ratio. Compared with the proposed allowable stress line, it has been confirmed that the existing JRIS standards' line is located excessively on the safety side and the EN standards' line cannot evaluate the safety when the stress ratio is high.

As described above, using the proposed allowable stress line makes it possible to rationally design wheel webs' fatigue strength when tread braking with a relatively high load is applied while securing sufficient safety.

References

1) High-speed Railway Wheel and Axle Study Committee: Railway wheel and axles. Maruzen Planet Co., Ltd., 2008
2) The Japan Association of Rolling Stock Industries: JRIS J 0405 (Rolling stock -Verification of the fatigue strength of the solid wheel web), 2010
3) EN 13979-1: Railway applications. Wheelsets and bogies. Monobloc wheels. Design assessment procedure. Part 1. Forged and rolled wheels. 2017
4) Ronchi, A. et al.: Application of EN-based design for non-European scenarios the case of Lucchini RS and JR WEST. Proceedings of the XIX International Wheelset Congress, 2019
5) Kato, T. et al.: Journal of the Society of Materials Science, Japan. 54 (12), 1275 (2005)
6) Kato, T. et al.: Transactions of the JSME (in Japanese). 87 (895), 20 (2021)
7) The Japan Society of Mechanical Engineers: Standard Method of Statistical Fatigue Testing (JSME S 002). 1994
8) The Society of Materials Science, Japan: Fatigue Design Handbook. Yokendo Ltd. Publishers, 1995
9) Wakuri, Y. et al.: Transactions of the JSME (in Japanese)-version C. 61 (583), 1123 (1995)

Takanori KATO
Dr. Eng., Chief Manager, Head of Dept.
Railway, Automotive & Machinery Parts Research Dept.
Kansai R & D Lab.
1-8 Fuso-Cho, Amagasaki City, Hyogo Pref. 660-0891

Miyuki YAMAMOTO
Dr. Eng., Professor
Graduate School of Engineering
Osaka University

Taizo MAKINO
Dr. Eng., Leading Researcher
Steel Research Laboratories

Yoshinari YAMAMURA
Railway Wheel & Axle Design & Development Section
Railway Wheel & Axle Designing Dept.
Railway Wheel, Axle & Bogie Div.
Kansai Works

Chihiro KOZUKA
Senior Manager
Railway Wheel & Axle Quality Design Section
Railway Wheel, Axle & Bogie Quality Control Dept.
Quality Management Div.
Kansai Works