

Fatigue Strength Evaluation Method for Welded Joints of Bogie Frames for Railway Vehicles

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Abstract

Bogie frames for railway vehicles are assembled by welding, and it is important to ensure fatigue strength at the welded joints. Nippon Steel Corporation has developed a new fatigue strength evaluation method for the welded joints of bogie frames. As a stress evaluation method, edge type gauge stress, which is independent of weld geometry and has less variation in measurement, was proposed. It was found that the fatigue strength of as-weld joints evaluated by the edge type gauge stress was higher than the allowable stress of the current JIS, which was assumed to have a fracture probability of 1.4%, based on the published literature data. Furthermore, a new fatigue life prediction method based on the partial safety factor method was proposed, and it is shown that this method can accurately predict the increase of fracture probability with lifetime.

1. Introduction

Bogie frames of railway vehicles are often assembled by welding components. These welds must have high strength and durability for long-term use. Currently, these requirements are met by designing according to JIS E 4207¹⁾ and JIS E 4208²⁾ and many years of experience. However, there have been some reports of fatigue damage in weld joints.³⁾ Fatigue design of welds is thus important to ensure the safety of bogie frames. In our study reported here, we have undertaken the following three initiatives to improve the fatigue design method for bogie frame welds, especially unfinished welds (hereinafter referred to as as-welds): (1) investigation of an appropriate method for evaluating the stress at the weld toes, which are likely to initiate fatigue cracks,⁴⁾ (2) evaluation of the relationship between the fatigue fracture probability of as-welds based on literature data and the allowable stress specified in JIS E 4207,⁵⁾ and (3) development of a new fatigue life prediction method for bogie frame welds by considering fatigue property variations and load variations.⁶⁾ The results of these three initiatives are summarized below.

2. Appropriate Stress Evaluation Method for Weld Toes⁴⁾

In the strength design of the as-welds of bogie frames, it is necessary to use an appropriate stress evaluation method assuming weld

toe shape variations. Although the hot spot stress⁷⁾ may be used as one measure for evaluating the stress of as-welds, it is difficult to apply the hot spot stress method as it is because bogie frames may not have sufficient space to determine the hot spot stress. In this chapter, we investigated an appropriate stress evaluation method by static load test and FEM analysis for the three strain gauge attachment types shown in **Fig. 1**. The characteristics of these attachment types are as follows: (a) JIS type: The as-weld surface to which a strain gauge is to be attached is finished curved with a radius of about 3 mm and the strain gauge is attached at the start of the machined curve; (b) center type: The center of the strain gauge is attached to the weld toe; and (c) edge type: The base edge of the strain gauge is attached to the weld toe. This chapter is produced based on our literature.⁴⁾

2.1 Static load test method

Cruciform joints made by welding plates were used as test specimens. The plate steel was SM490YB, which is used for bogie frames, and the weld metal was JISYGW-19. The shape of the specimen is shown in **Fig. 2**. The curvature radius of the weld toe ranged from 1.6 to 4.8 mm, with an average of 3.1 mm and a standard deviation of 0.58 mm.

In the static load test, a tensile load of 25 kN was applied to the

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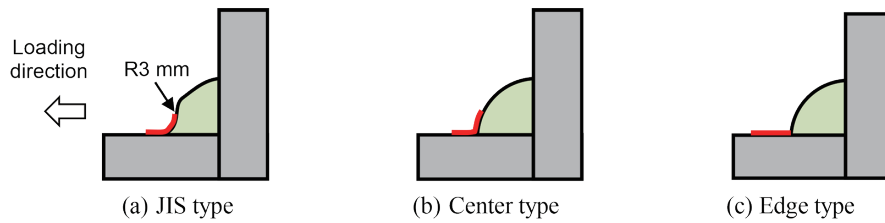


Fig. 1 Strain gauge attachment positions⁴⁾

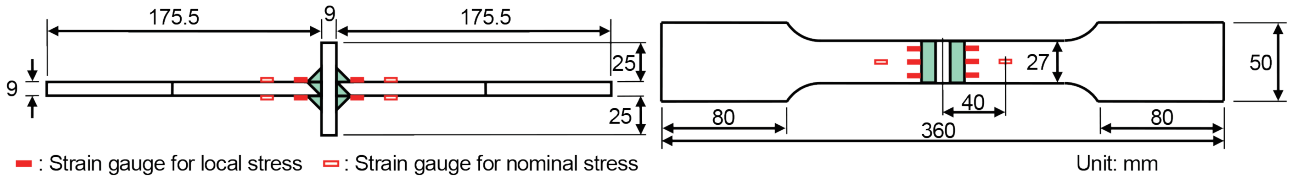


Fig. 2 Schematic illustration of cruciform welded joint test specimen⁴⁾

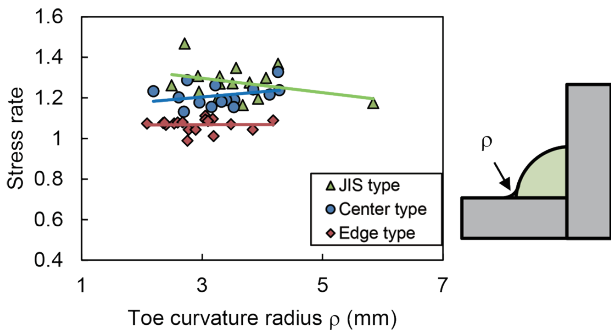


Fig. 3 Stress rates with different toe curvature radii⁴⁾

specimen. First, the stress was measured using the center type and edge type methods. The specimen was then machined to a radius of 3 mm, and its stress was measured by the JIS type method. The stress was determined by multiplying the measured strain by the Young’s modulus of 206 GPa (hereinafter referred to as the gauge stress).

2.2 Results of static load test

For each gauge attachment method, the ratio of the nominal stress measured at a position sufficiently far from the weld toe to the gauge stress was obtained (this ratio is hereinafter referred to as the stress rate). **Figure 3** shows the relationship between the stress rate and the weld toe curvature radius (the machined radius for the JIS type). For the JIS type method, the weld toe is machined to a radius of 3 mm, but the radius varies, and the stress rate also varies greatly. For the center type method, no clear correlation is observed between the stress rate and the weld toe curvature radius, but the stress rate can be confirmed to vary at the same weld toe curvature radius. For the edge type method, on the other hand, the stress rate is almost constant, regardless of the weld toe curvature radius, and varies little. **Table 1** shows the average stress rate and the coefficient of variation. The stress rate for the edge type is the smallest of the three types in terms of both average value and coefficient of variation. For the JIS type, both the average value and coefficient of variation are the largest of the three types. The center type falls between the other two types. The average value for the center type is almost the same

Table 1 Stress rates of the welded joint test specimens⁴⁾

Strain gauge attachment type	Average	Coefficient of variation
JIS type	1.28	0.061
Center type	1.21	0.042
Edge type	1.07	0.028

*Stress rate: Stress at weld toe / stress at position 40 mm from weld center

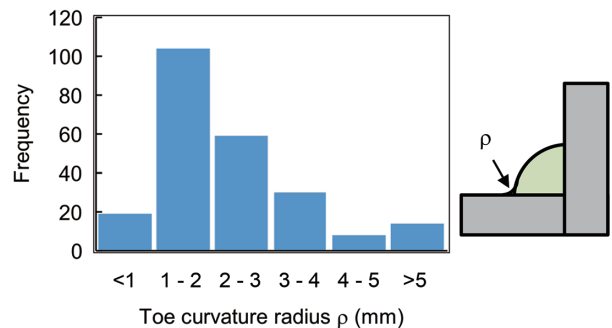


Fig. 4 Frequency of toe radius at weld toes in bogie frame⁸⁾

as that for the JIS type.

The relationship between the stress rate and the weld toe curvature radius has been evaluated above. It is also necessary to understand the scatter of the weld toe curvature radius in actual bogie frames. Therefore, we prototyped bogie frames and measured the weld toe curvature radius of 234 welds in the prototype bogie frames. **Figure 4** shows the frequency distribution of the measured weld toe curvature radius. As Fig. 4 shows the weld toe curvature radius varies greatly and there is a certain proportion of relatively small weld toe curvature radii of less than 1 mm.

2.3 Discussion of gauge attachment methods

The static load test results showed that the scatter of the gauge stress is large for the JIS type and small for the edge type. Here, we discuss the effect of the gauge attachment position as one responsible factor.

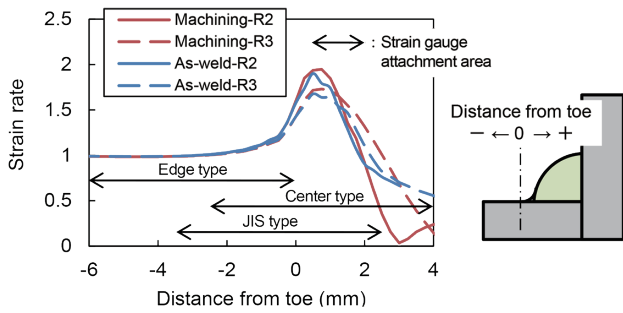


Fig. 5 Strain rate distributions around weld toes⁴⁾

Figure 5 shows the distribution of the ratio of the principal strain in the surface near the weld toe to the principal strain apart from the weld toe (hereafter referred to as the strain rate) as obtained from FEM analysis and the gauge attachment range. In the case of the JIS type and the center type, the strain rate is high in large areas in the gauge attachment range and varies greatly. This finding points to the possibility that the measured stress may vary greatly depending on the attachment position. For the edge type, on the other hand, the strain rate changes little in the gauge attachment range, even though the weld toe curvature radius is different. For this reason, we consider that the stress rate measured by the edge type was almost constant regardless of the weld toe curvature radius and varied little.

As described above, in the as-welds, the edge type is a strain gauge attachment method with a minimum of scatter, making it highly suitable for practical application. Therefore, the edge type is considered as an appropriate stress evaluation method for the strength design of as-welds in bogie frames.

3. Fatigue Strength Evaluation of Bogie Frame Welds⁵⁾

To apply the edge type stress evaluation method proposed in the previous chapter to the fatigue design of welds in bogie frames, we must use an appropriate allowable stress. Therefore, it is first necessary to understand to what extent the allowable stress specified in JIS E 4207, which is the current bogie frame design method, corresponds to the fracture probability when evaluated using the edge type stress. In this chapter, we calculated the allowable stress using the edge type and based on the fatigue test data collected from published literature.

The edge type evaluation stress was determined based on the results of the numerical analysis of simulated fatigue testing. The number of prepared data was 18 sets and 126 points for cruciform joints (Fig. 6) and 11 sets and 110 points for out-of-plane gusset joints. The data in Fig. 6 have a relatively large scatter (coefficient of variation) as described later. One possible reason is that various weld toe curvature radius data are included. The allowable stress specified in JIS E 4207 does not indicate the applicable range of the weld toe curvature radius in particular. It is thus considered reasonable to evaluate the allowable stress using the data of Fig. 6. The allowable stress was obtained by setting various fracture probabilities and performing a statistical analysis of the fatigue data and was then compared with that of JIS E 4207.¹⁾ In the statistical analysis, we used a method assuming normal distribution and a method called the probit method, which can also consider the test data for cracks not yet occurring. Details of the reproduction analysis and statistical analysis are described in our literature.⁵⁾ The description in this chapter summarizes the results based on our literature.

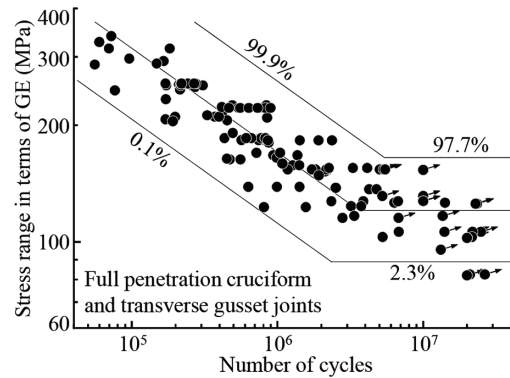


Fig. 6 S-N diagram in terms of edge type gauge stress based on the collected cruciform joint fatigue test data⁵⁾

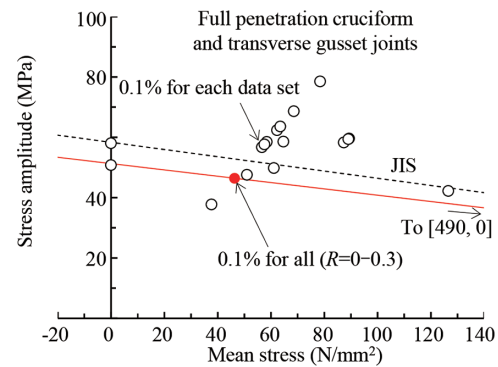


Fig. 7 Relationship between fatigue strength (0.1% fracture probability) and JIS allowable stress obtained from fatigue data analysis⁵⁾

When the allowable stress obtained from each data set was organized as the mean stress along the horizontal axis of Fig. 7, the fatigue strength was lower than the JIS E 4207 allowable stress for 5 out of 18 sets of cruciform joints and 5 out of 12 sets of out-of-plane gussets. The allowable stress was set to a value equivalent to a 0.1% fracture probability at 2 million cycles in the same way as described in JIS E 4207. The difference in the evaluation stress between JIS E 4207 and the edge type was taken into account by dividing the allowable stress by 1.2.⁴⁾

Furthermore, when all the data for cruciform joints were analyzed as a group, as shown in Fig. 6, the allowable stress obtained was 51.3 MPa in amplitude and was 12% smaller than that specified in JIS E 4207 (Fig. 8). The allowable stress was assumed under the same conditions as described above. When the allowable stresses corresponding to a 2.3% fracture probability at 10 million cycles and to a 0.1% fracture probability at 10 million cycles, that is, the allowable stresses that ensure longer use, were calculated, they were respectively 48.8 MPa (-16% compared to JIS E 4207) and 41.2 MPa (-29% compared to JIS E 4207). The allowable stresses calculated based on the data for out-of-plane gusset joints were even smaller (Table 2).

When the degree of data scatter (coefficient of variation) was examined, it was 0.13 for the cruciform joints and 0.10 for the out-of-plane gusset joints in the results described here and was larger than 0.06 presumed in JIS E 4207. This is because multiple data sets with different welding conditions were collected, and the overall variance was considered. This situation is thought to be one factor

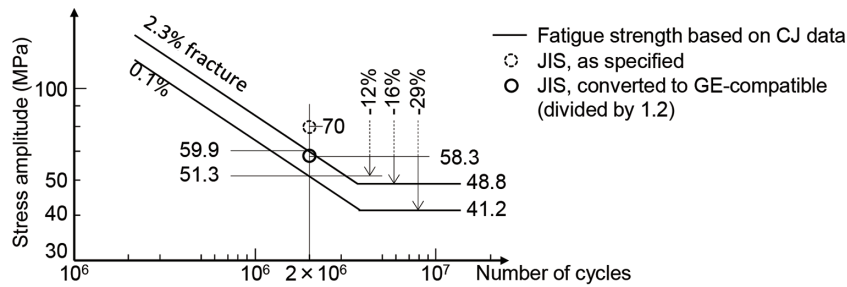


Fig. 8 Relationship between fatigue design curves (0.1%/2.3% fracture probability) and JIS allowable stresses obtained from fatigue data analysis⁵⁾

Table 2 Fatigue data analysis results⁵⁾

Fatigue strength	Cruciform	Out-of-plane gusset
(a) at 2×10^6 , 0.1% fracture	92.8 (51.3)	89.7 (49.4)
(b) at 2×10^6 , 5% fracture by IIW Recom.	110.1 (62.0)	103.0 (57.6)
(c) Design vs. this study's results	1.14 ^a	1.18 ^a

^a Ratios of JIS (70/1.2=58.3) to (a)

responsible for the relatively small allowable stresses obtained. In reality, we design joints that are welded under various conditions, so the results reported here are considered to reflect the actual situations well.

Conversely, the allowable stress of 58.3 MPa specified in JIS E 4207 corresponds to a fracture probability of 1.4%, according to the fatigue data in this study. The fracture probability of 1.4% is larger than the originally supposed fracture probability of 0.1%. This result suggests that we must take care in setting the loading conditions when we use the allowable stress specified in JIS E 4207.

4. New Fatigue Life Prediction Method Based on Partial Safety Factor Method^{6,9)}

Since the fatigue limit design is adopted for bogie frames, they are often mistakenly thought to have an infinite fatigue life. However, because fatigue damage can occur even at stresses below the fatigue limit, the bogie frames actually have a finite fatigue life. Also, as described in the previous chapter, the allowable stresses currently specified are such that fatigue cracks will occur with a certain probability. On the other hand, a fatigue life assessment method under actual operation was proposed in the past,¹⁰⁾ but it cannot consider factors such as mean stress and weld toe curvature radius. For this reason, we studied a new fatigue life prediction method based on the latest fatigue test data and on JIS B 9955¹¹⁾ published in 2017, and JSME S 018¹²⁾ published in 2018, i.e., the partial safety factor method. This chapter is compiled from our previous reports.^{6,9)}

4.1 Study of $S-N$ curves for fatigue life evaluation

This section evaluates as-welded joints as discussed in the previous chapter. In the past, we prepared cruciform welded joints under similar welding conditions. We used the same steel plates (SM400B and SM490YB with a plate thickness of 9 mm) as those used in the railway bogie frames manufactured by Nippon Steel Corporation. We then conducted the fatigue tests of the cruciform welded joints. The test results are evaluated as the $S-N$ diagram in Fig. 9. The equivalent stress amplitude converted by the Smith-Watson-Topper (SWT) method¹³⁾ (hereinafter referred to as the SWT stress) is plotted along

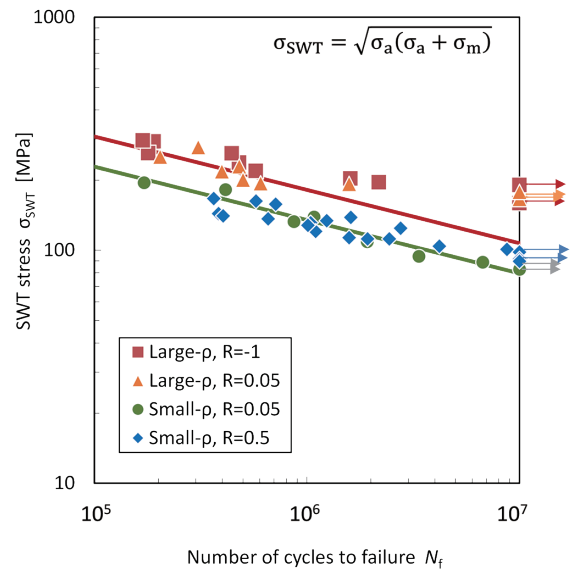


Fig. 9 $S-N$ diagram modified using the SWT method^{6,9)}

the vertical axis in the $S-N$ diagram and is given by:

$$\sigma_{\text{SWT}} = \sqrt{\sigma_a \cdot \sigma_{\text{max}}} = \sqrt{\sigma_a (\sigma_a + \sigma_m)} = \sqrt{\frac{2}{1-R}} \sigma_a \quad (1)$$

where σ_a is the stress amplitude, σ_{max} is the maximum stress, and σ_m is the mean stress. These values were all measured by the edge gauge method described in the previous chapter. R is the stress ratio.

In Fig. 9, the plot points are divided into different types according to the weld toe curvature radius magnitude and stress ratio. In Fig. 9, Large- ρ indicates a weld toe curvature radius of 1.6 to 3.3 mm with an average of 2.6 mm, and Small- ρ indicates a weld toe curvature radius of 0.2 to 1.5 mm with an average of 0.6 mm. Figure 9 shows that the plot points are grouped according to the curvature radius magnitude and that no fatigue life difference with the stress ratio is observed in the respective plot point groups. The explanation of the latter observation is omitted in this report. When the $S-N$ curves were described according to the stress amplitude, the fatigue life varied with the stress ratio. This finding means that the effect of the stress ratio was accurately considered by the SWT method. For this reason, the $S-N$ curves were approximated for the plot point groups with the small and large curvature radii, respectively.

$$N = A \cdot \sigma_{\text{SWT}}^{-4.375}, A = 2.080 \times 10^{15} \text{ (Small-}\rho\text{)}, 7.656 \times 10^{15} \text{ (Large-}\rho\text{)} \quad (2)$$

Where N is the number of cycles (or fatigue life), and the unit of σ_{SWT} is MPa. From the ratio of A in the above equation, it can be

seen that the fatigue life for Large- ρ is 3.68 times that for Small- ρ . The exponent m of the $S-N$ curve in Eq. (2) is 4.375, which is larger than that of the previously proposed m value of 3.^{7,10} This result is expected because previous studies approximated $S-N$ curves from the data covering various plate thicknesses and weld toe curvature radii. In Fig. 9, the m value becomes 2.545 when it is approximated from all the data grouped together, regardless of the weld toe curvature radius. In this case, the m value is small, so the fatigue life in the long fatigue life range may be underestimated, and the scatter may be overestimated. For this reason, we think that we can predict the fatigue life more rationally if we limit the plate thicknesses to the thicknesses of plates used in bogie frames and use $S-N$ curves distinguished by the weld toe curvature radius as shown in Eq. (2). From the scatter of the plotted points in Fig. 9, 0.4113 was obtained as the standard deviation $S_{\ln N}$ of the natural logarithm $\ln N$ of the fatigue life. Since the values for Large- ρ and Small- ρ were close to each other, the average of the two values was adopted. Using this average value, a fatigue life curve that takes into account the scatter, i.e., a $P-S-N$ curve, can be obtained. In Chapter 3, we integrated the test data from various organizations and obtained the $P-S-N$ curves of Fig. 6 to evaluate the fatigue strength at 2 million cycles and the fatigue limit at 10 million cycles with their statistical variabilities to study the allowable stress. In this section, however, let us add that we obtained new $P-S-N$ curves for fatigue life evaluation by using the experimental data of only Nippon Steel in order to aim for more rational fatigue life prediction and that the weld toe curvature radius differentiates the new $P-S-N$ curves.

4.2 Fatigue life prediction method based on partial safety factor method

The partial safety factor method is a method of defining partial safety factors for load and strength and evaluating reliability based on standard equations containing such factors, i.e., determining the fracture probability.^{11,12} This method enables deterministic reliability evaluation without conventionally cumbersome probability calculations. However, the partial safety factor method is intended for

fracture evaluation and its application to fatigue has been dealt with in a few studies in the past.¹⁴ Therefore, in this report, we introduced the following two new concepts for applying the partial safety factor method to fatigue fracture evaluation. One is the use of the accumulated damage value and its limit value as evaluation parameters. The other is the use of interval estimation based on the t-distribution to estimate the scatter of the damage value.

Figure 10 shows an image of applying the partial safety factor method to fatigue. First, as shown in the upper part of Fig. 10, the accumulated damage value D is calculated based on the modified Miner’s rule, which is a linear damage rule and is used as an evaluation parameter on the load side. To calculate the accumulated damage value D , a running test is conducted using an actual vehicle. The obtained stress measurement data are divided into mean stress-stress amplitude combinations and frequencies using the rainflow method. These results are substituted into Eq. (1) to obtain the SWT stress frequency distribution. Then, the fatigue life N_i and frequency n_i calculated from Eq. (2) are substituted into the following Eq. (3) to obtain the section damage value D' .

$$D' = \sum_i \frac{n_i}{N_i} \tag{3}$$

where D' is the damage value in each of the 10 or more equidistant sections into which the round trip data from the test line are divided. The damage values D' in all sections are totaled to obtain the accumulated damage value D that considers the damage to the bogie frame throughout its mileage and life. When the mileage at which the value D thus obtained reaches the critical value D_{cr} , it is inversely calculated, and the predicted fatigue life is obtained. When D_{cr} is set to 1.0, it becomes the predicted fatigue life when the scatters on both the load side and the strength side shown in the upper part of Fig. 10 are not taken into account.

Next, the $P-S-N$ curve obtained in Section 4.1 is used to consider the scatter on the strength side. In Section 4.1, the logarithmic standard deviation $S_{\ln N}$ of the fatigue life was clarified. Since D_{cr} is also defined as the fatigue life ratio, the logarithmic standard deviation $S_{\ln D_{cr}}$ of D_{cr} is the same as $S_{\ln N}$. Therefore, if the logarithmic

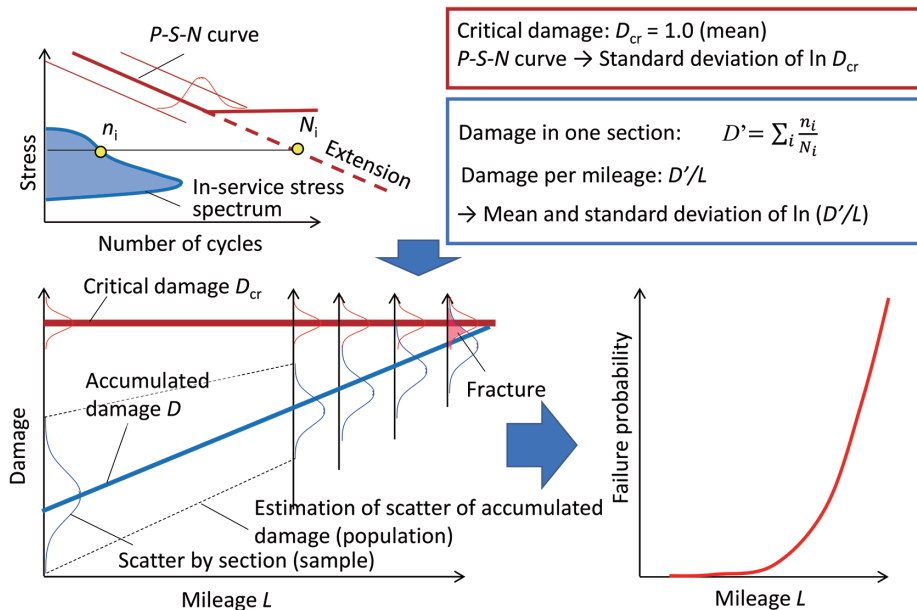


Fig. 10 Application of the partial safety factor method to the fatigue fracture issue^{6,9}

normal distribution of D_{cr} is obtained using $S_{ln D_{cr}}$ and D_{cr} of the occurrence probability according to this distribution is used as the limit value, it becomes possible to predict the fatigue life by considering the scatter on the strength side. This method considers only the scatter of D_{cr} indicated by the red line in the lower left of Fig. 10, considering only the center of blue-lined D and not considering the scatter of D .

Finally, we consider the scatter on the load side. As the sample data on the load side, we use the damage value D' for each section as described above. Although D' varies widely, the accumulated damage value required for fatigue life prediction should asymptotically approach the average of D' per unit mileage multiplied by the mileage. Therefore, using the scatter of D' as is would result in an overestimation of the scatter. For this reason, the interval estimation method based on the t-distribution was used in this report. The interval estimation method is a probabilistic method of obtaining the average scatter of the population from the scatter of the sample data. Here, the population is the accumulated damage value D of the test bogie through its fatigue life. According to this method, the standard deviation $S_{ln D}$ of D can be calculated by substituting the standard deviation $S_{ln D'}$ of D' into the following Eq. (4):

$$S_{ln D} = t_{0.1587} \frac{S_{ln D'}}{\sqrt{n_s}} \tag{4}$$

where $t_{0.1587}$ is obtained from the t-distribution table by considering the number of degrees of freedom $n_s - 1$ where n_s is the sample size. In Eq. (4), $S_{ln D}$ is smaller than $S_{ln D'}$. Thus, it becomes possible to estimate that the scatter of blue-lined D in the lower left of Fig. 10 decreases with mileage.

In the lower left of Fig. 10, the area of the region where the probability distributions of D_{cr} and D overlap corresponds to the fracture probability. As the mileage increases, the area of the overlap region increases, and so does the fracture probability, as shown in the lower right of Fig. 10. Complicated calculations were previously required to determine the area of the overlap region, i.e., the fracture probability. The partial safety factor method can now be used to calculate the fracture probability relatively simply and deterministically.

Figure 11 shows the concept of reliability evaluation by the partial safety factor method. The vertical axis shows load, and the horizontal axis shows strength. The probability distribution of the combination of the two is expressed as a three-dimensional contour map with the average of the two at the vertex. The limit state function G is expressed as a 45° line passing through the origin and where the

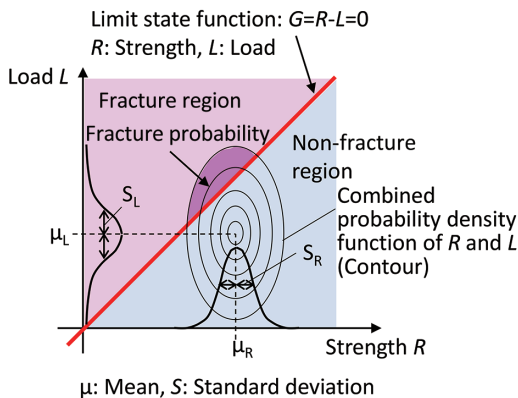


Fig. 11 Concept of reliability evaluation using the partial safety factor method^{6,9)}

strength and load are equal. Since a fracture occurs in the upper left of G , that is, in the region where the load is greater than the strength, the sum of the probability distribution in this fracture region corresponds to the fracture probability. Furthermore, although details are omitted, if Fig. 11 is converted to standard normalized coordinates, that is, the average is 0, and the standard deviation is 1, it becomes possible to calculate the fracture probability from the distance between G and the origin using a normal distribution table. Therefore, if the strength in Fig. 11 is replaced by the critical damage value D_{cr} and the load is replaced by the accumulated damage value D , the fatigue fracture probability can be calculated. Furthermore, it is possible to predict how the fracture probability changes with the mileage, that is, the fatigue life.

4.3 Results of fatigue life prediction

The fatigue life of an actual bogie frame was predicted by the method proposed in the previous section. As-welds in the bogie frame obstacle deflector arm were evaluated. The round-trip data of the test line were divided into 32 sections. The damage value in each section and the mean and standard deviation $S_{ln D'}$ of the damage value were obtained. Then, using the interval estimation method according to the t-distribution described in the previous section, $S_{ln D}$ and n_s (=32) were substituted into Eq. (4) to obtain the mean and standard deviation $S_{ln D}$ of the accumulated damage value. In this case, $S_{ln D}$ was 18% of $S_{ln D'}$. The fatigue life and fatigue fracture probability were predicted by applying the mean and standard deviation of the accumulated damage value obtained in this way and the mean and standard deviation of the critical damage values obtained in Sections 4.1 and 4.2 to the partial safety factor method described in Section 4.2 and Fig. 11. Figure 12 shows the prediction results for Small- p . The prediction results show that the fracture probability increases with fatigue life and that shorter fatigue life is predicted with a 50% lower fracture probability when the scatter of both strength and load are considered than when the scatter of strength alone is considered.

4.4 Advantages and practical application images of proposed fatigue life prediction method

Railway bogie frames have been traditionally assumed to have about 20 years of fatigue life if they satisfy their design criteria¹⁾. However, there are rare cases where fatigue fractures occur before that. As mentioned before, some railway operators use bogie frames for longer periods of time as if they have infinite life. In this situation, we had an opportunity to predict the fatigue life of bogie frames and had to assume a large error range with respect to the pre-

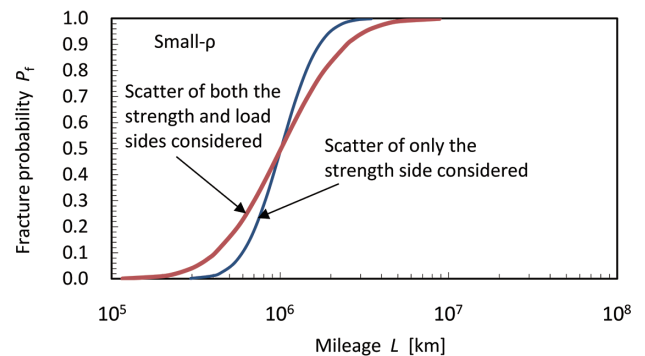


Fig. 12 An example of the lifetime prediction result^{6,9)}

dicted fatigue life when we used a conventional fatigue life prediction method. When we use the fatigue life prediction method described in this report, we can present how the fracture probability will change in the predicted fatigue life range. Thus, we can propose reasonable bogie replacement intervals and use the fatigue life prediction method as a tool to ensure the fatigue safety of currently used bogie frames. Our fatigue life prediction method is also expected to be useful in proposing newly designed bogies that are suitable for longer-term use. Also, Nippon Steel has developed a monitoring bogie and has been working to monitor how the monitoring bogie is used constantly.¹⁵⁾ When the stress data measured and evaluated with the monitoring bogie are applied to the fatigue life prediction method, we can understand in advance the change in the fatigue life with the change in usage and aging of the bogies.

5. Conclusions

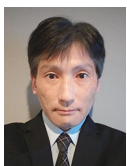
To improve the fatigue design method for as-welds in railway vehicle bogie frames, we investigated a stress evaluation method, allowable stress, and fatigue life prediction method. We proposed a new stress evaluation method using edge strain gauges and demonstrated that the new stress evaluation method has a smaller measurement scatter than conventional stress evaluation methods. We also evaluated the fatigue strength of as-welds in bogie frames by the stress measured with edge strain gauges and based on published literature data and compared the fatigue strength with the allowable stress specified in JIS E 4207. We clarified that the allowable stress specified in JIS E 4207 corresponds to a fatigue fracture probability of 1.4% and that the fatigue fracture probability of 1.4% was higher than that originally thought in JIS E 4207. Furthermore, we proposed a new fatigue life prediction method based on the partial safety factor method. The partial safety factor method can be used to accurately predict the increase in the probability of fracture with fa-

tigue life.

As noted above, Nippon Steel, as a steel manufacturer, is clarifying the fatigue strength of materials, including welds, and would like to propose improvements to the reliability of bogies by applying the knowledge it has gained in other fields to bogie frames. Since the standardization of these improvements is important to improve safety in the railway industry, we will also work to achieve this objective.

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