Fatigue Evaluation of Railway Vehicle Bogie Frame by Different Methods

Fan-Song LI*, Ping-Bo WU, Yi-Zhao NIE, Ye SONG

Southwest Jiaotong University, No.111, North 1st Section of Second Ring Road, Chengdu City, Sichuan Province, China

lifansong2013@163.com

*Corresponding author

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Abstract: The fatigue strength of a railway vehicle bogie frame is evaluated by different methods, which include endurance limit approach and cumulative damage approach. Haigh-Goodman and Smith-Goodman diagram in general standards are used in endurance limit approach, and four linear damage methods are considered in cumulative damage approach. During the evaluation, finite element method (FEM) and line test method are used to compare the two different evaluation approaches, while the line test dynamic stress is modified by mean stress calculated in FEM software. The comparison results illustrate that Haigh-Goodman and Smith-Goodman are identical when consider same safety factor, but the Goodman diagram in JIS standard are conservative relative to that in UIC standard. The elementary S-N curve is too conservative to reflect real situation, and the Haibach modified S-N curve are recommended when using cumulative damage approach.

Introduction

The bogie is one of the most important railway vehicle part, while the bogie frame is the main bearing structure in vehicle system. Due to its importance, many scholars have been studied the fatigue strength. Jung Seok Kim utilizes the Haigh-Goodman diagram to evaluate a bogie frame fatigue safety based on test and simulation[1, 2], Baek uses the P-S-N curve to predict the fatigue life of a bogie frame[3], Dietz combines the multi-body system (MBS) and finite element method to calculate the dynamic loads, which used to evaluate the fatigue strength of a frame[4], Lucanin evaluates a bogie frame which appear cracks by Smith-Goodman diagram [5], and Jeon uses the Haigh-Goodman diagram to evaluate fatigue strength of a bogie frame made by Glass Fiber Reinforced Polymer[6]. Moreover, the fatigue strength evaluation methods of bogie frame are stipulated in many international general standards. For example, UIC 615[7], JIS E 4207[8], ORE B12/RP60[9] and EN 13749[10]. Among the general standards, two main approaches are widely introduced and used; they are endurance limit approach and cumulative damage approach. However, the specific fatigue evaluation methods in different standards are somewhat different. Study on the different fatigue evaluation approaches are contributed to recognize the characteristic and application range of different standards, and also ensure the bogie frame safety during design stage.

Fatigue Strength Evaluation Approach

Endurance Limit Approach

This approach can be used for areas where all dynamic stress cycles remain below the material endurance limit. Although there are too many kinds mean stress correction methods, among the correction methods, the Goodman formula is simple and works well for tensile normal mean stress situations, so Goodman correction is only concerned in this paper. Goodman diagram has two common diagrams, Haigh-Goodman and Smith-Goodman, which are shown in Figure 1. The Haigh and Smith Goodman diagram all have two types, one considers that the compressive normal mean stress increases the fatigue limit while the other one ignore the compressive normal stress effect, the latter will produce conservative result. The Goodman correction formula is

$$\sigma_{-1}^{'} = \sigma_{-1} \cdot (1 - \sigma_m / \sigma_b)^{-1} \tag{1}$$

Where σ-1 is the fatigue limit for fully reversed loading, σ-1 is the mean stress, and σb is the tensile strength. Nowadays, the Goodman diagrams in standards are modified by yield strength which as an additional constraint for diagram, specific in Figure 1.

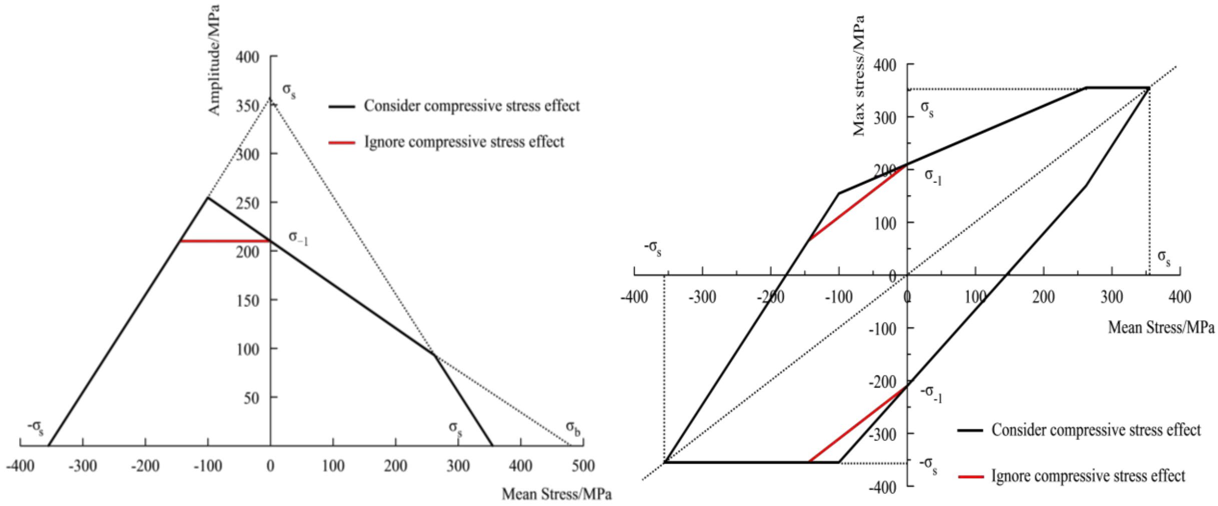


Fig.1 The Haigh-Goodman Diagram and Smith-Goodman Diagram

The permissible stress amplitude at different mean stress is calculated in this paper, which shown in Table 1 and Table 2.

As shown in Table 1 and Table 2, the Goodman diagram has four sections when ignore compressive stress effect, while three sections when consider the increasing effect of compressive stress. From the permissible stress amplitude formula in the paper, the Haigh and Smith Goodman diagram have the identical evaluation result.

When evaluate the fatigue strength of bogie frame, all appropriate combinations of the normal service load cases provided in norm or measurement results determined in accordance with the guidelines remain should below the material endurance limit or inside the Goodman diagram. When stress amplitudes of all points concerned are inside the evaluation diagram, it means that the structure satisfy infinite life design criterion.

It should be noted that the load cases provided in standard are normal service loads, which are common and not large enough. So it is permissible for stress cycles due to exceptional load cases to exceed the endurance limit since, by definition, they do not occur sufficiently often to significantly affect the fatigue life. But it is different for user to know the impact of the exceptional load cases, so the other approaches are essential to evaluate the fatigue strength.

Tab. 1 Permissible Stress Amplitude when Ignore Compressive Stress Effect

Mean stress	Permissible stress amplitude	
	Smith-Goodman	Haigh-Goodman
$-\sigma_s \le \sigma_m \le \sigma_{-1} - \sigma_s$	$\sigma_a \le \sigma_m + \sigma_s$	$\sigma_a \le \sigma_m + \sigma_s$
$\sigma_{-1} - \sigma_s \le \sigma_m \le 0$	$\sigma_a \le \sigma_{-1}$	$\sigma_a \le \sigma_{-1}$
$0 \le \sigma_m \le \sigma_b \cdot \frac{(\sigma_s - \sigma_{-1})}{(\sigma_b - \sigma_{-1})}$	$\sigma_a \le -\left(\frac{\sigma_{-1}}{\sigma_b}\right) \cdot \sigma_m + \sigma_{-1}$	$\sigma_a \le -\left(\frac{\sigma_{-1}}{\sigma_b}\right) \cdot \sigma_m + \sigma_{-1}$
$\sigma_b \cdot \frac{(\sigma_s - \sigma_{-1})}{(\sigma_b - \sigma_{-1})} \le \sigma_m \le \sigma_s$	$\sigma_a \le -\sigma_m + \sigma_s$	$\sigma_a \le -\sigma_m + \sigma_s$

Tab. 2 Permissible Stress Amplitude Consider Compressive Stress Effect

Mean stress	Permissible stress amplitude	
	Smith Goodman	Haigh Goodman
$-\sigma_s \le \sigma_m \le \sigma_b \cdot \frac{(\sigma_{-1}-\sigma_s)}{(\sigma_b+\sigma_{-1})}$	$\sigma_a \le \sigma_m + \sigma_s$	$\sigma_a \le \sigma_m + \sigma_s$
$\sigma_b \cdot \frac{(\sigma_{-1}-\sigma_s)}{(\sigma_b+\sigma_{-1})} \le \sigma_m \le \sigma_b \cdot \frac{(\sigma_s-\sigma_{-1})}{(\sigma_b-\sigma_{-1})}$	$\sigma_a \le -\left(\frac{\sigma_{-1}}{\sigma_b}\right) \cdot \sigma_m + \sigma_{-1}$	$\sigma_a \le -\left(\frac{\sigma_{-1}}{\sigma_b}\right) \cdot \sigma_m + \sigma_{-1}$
$\sigma_b \cdot \frac{(\sigma_s-\sigma_{-1})}{(\sigma_b-\sigma_{-1})} \le \sigma_m \le \sigma_s$	$\sigma_a \le -\sigma_m + \sigma_s$	$\sigma_a \le -\sigma_m + \sigma_s$

Cumulative Damage Approach

Where a material has no defined endurance limit or some repetitive stress cycles exceed the limit, the cumulative damage approach shall be followed. This approach is an alternative to the endurance limit approach. Representative histories for each load case shall be expressed in terms of magnitude and number of cycles. Due regard shall be given to combinations of loads which act in unison. The damage due to each such case in turn is then assessed, using an appropriate material stress-cycle diagram, and the total damage determined in accordance with an established damage accumulation hypothesis.

Four kind of S-N curves are concerned in the paper, they are standard 1 which from IIW recommendations [11], standard 2 from Eurocode 3 standard [12], elementary type S-N curve from reference [13] and Haibach modified S-N curve from reference [14]. As shown in Figure 2, the conservatism of the four kinds S-N curve in descending order is elementary type, Haibach modified curve, standard 2 curve and standard 1 curve.

Only weld seam fatigue strength is evaluated, so the characteristic of the weld S-N curve is shown in Figure 2. The first knee point of the S-N curve is 5×106, and the second knee point of which is 108. Standard 1 curve and Haibach modified curve have one knee point, standard 2 curve has two knee curves, while the elementary type curve has no knee curve.

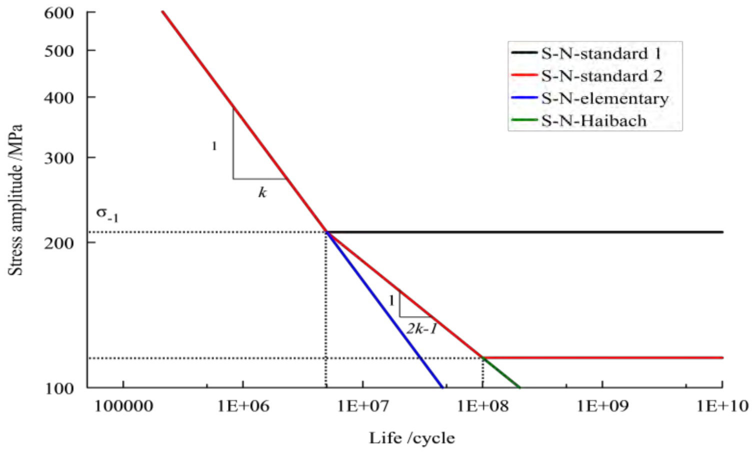


Fig. 2 Four Types S-N Curves of Bogie Frame Weld Seams

Fatigue Strength Evaluation by FEM Simulation

The loads of the bogie frame are calculated by UIC 615, which contain vertical loads, transverse loads, longitudinal loads from car body, and dynamic loads by vibration of motors or gearboxes.

The vertical loads at air spring mounting seats are

$$F_z = \frac{g}{2n_b}(m_{all} - n_b m_b) \tag{2}$$

The dynamic vertical loads are considered

$$F_{zq1} = F_{zq2} = \pm\alpha \cdot F_z \tag{3}$$

$$F_{zd1} = F_{zd2} = \pm\beta \cdot F_z \tag{4}$$

The transverse loads from carbody are

$$F_{yq} = 0.25 \times (F_z + 0.5 \cdot m_b g) \tag{5}$$

The dynamic loads from carbody are

$$F_{yd} = 0.25 \times (F_z + 0.5 \cdot m_b g) \tag{6}$$

The dynamic longitudinal loads from carbody are

$$F_{xd} = 0.1 \times (F_z + 0.5 \cdot m_b g) \tag{7}$$

Where g is the gravity acceleration, equal to 9.81 m/s2, nb is the number of bogies in one vehicle, equal to 2, mall is the weight of the vehicle, equal to 57 tons, mb is the weight of a bogie, equal to 6.6 tons in the calculation, while α=0.1, β=0.2. In addition, 3 times weight dynamic loads of motors and gearboxes are considered, and 5 ‰ curve irregularity is added during FEM simulation.

The combination of working conditions are provided in UIC 615, after simulation, the maximum stress σmax and the minimum stress σmin of weld seams are obtained, one working condition stress nephogram is given in Figure 3.

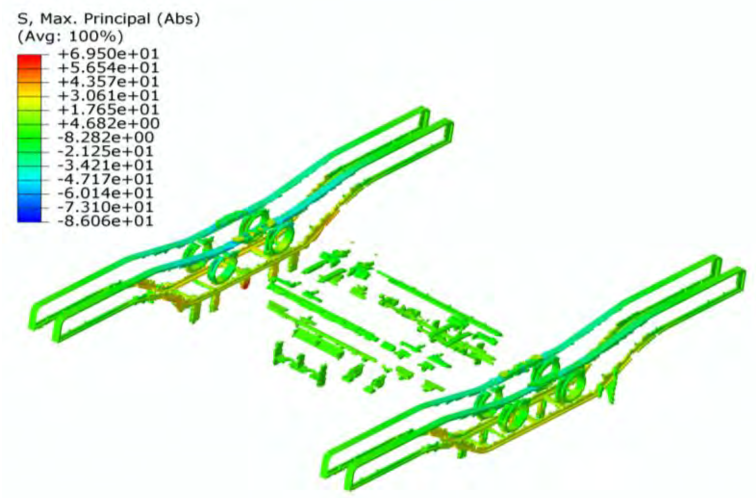


Fig. 3 The Stress Distribution of Weld seams in One Working Condition

The maximum and minimum stress obtained could be used for computing mean stress σm and stress amplitude σa by the formula

$$\sigma m = (\sigma max + \sigma min)/2 \tag{8}$$

$$\sigma a = (\sigma max - \sigma min)/2 \tag{9}$$

The fatigue strength of bogie frame could be evaluated by Goodman after acquiring σmax, σmin, σm and σa. The Haigh-Goodman diagram is from JIS E 4207 while the Smith-Goodman diagram is from ORE B12/RP60, because the two type's diagrams are recommended separately in the two norms. The evaluation results are shown in Figure 4.

From the result in Figure 4, the stress amplitude of calculated points is all inside the envelope line, so the fatigue strength is achieved. Nevertheless, the safety factor of Haigh-Goodman diagram in JIS E 4207 is 2.0 while that in ORE B12/RP60 is 1.65, so the JIS standard are conservative relative to ORE standard.

Because the load provided in norms are not load spectrum, so the cumulative damage approach could not be used; only line test results are evaluated by cumulative damage approach.

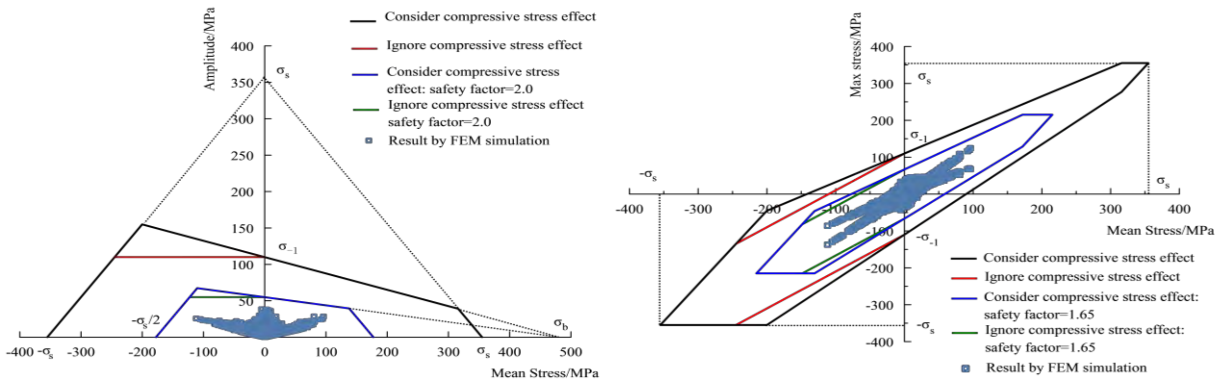


Fig. 4 Evaluation Result of Weld Seams by Goodman Diagram

Fatigue Evaluation by Line Test

By Endurance Limit Approach

The evaluation processes are identical except that the stress is obtained by line test. During the FEM simulation, the points concerned could be more as expected. While in line test, the number of concerned points is less than that in FEM simulation. In this paper, 46 test points are evaluated by Goodman diagram. However, the test results by line test have no initial mean stress, so, in this chapter, the stress spectrums are modified by mean stress (shown in Table 3) calculated by FEM software, the static vertical forces are only considered in modified program. After modified by FEM software, the test points are evaluated by two types Goodman diagrams, which shown in Figure 5, and the comparison between FEM simulation and line test are shown in Figure 6.

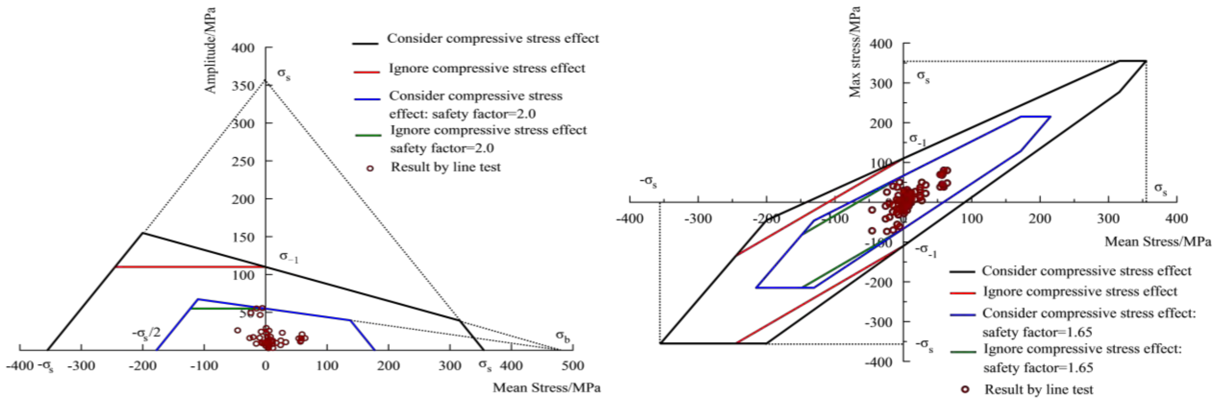


Fig. 5 Evaluation Results of Weld Seams by Goodman Diagram

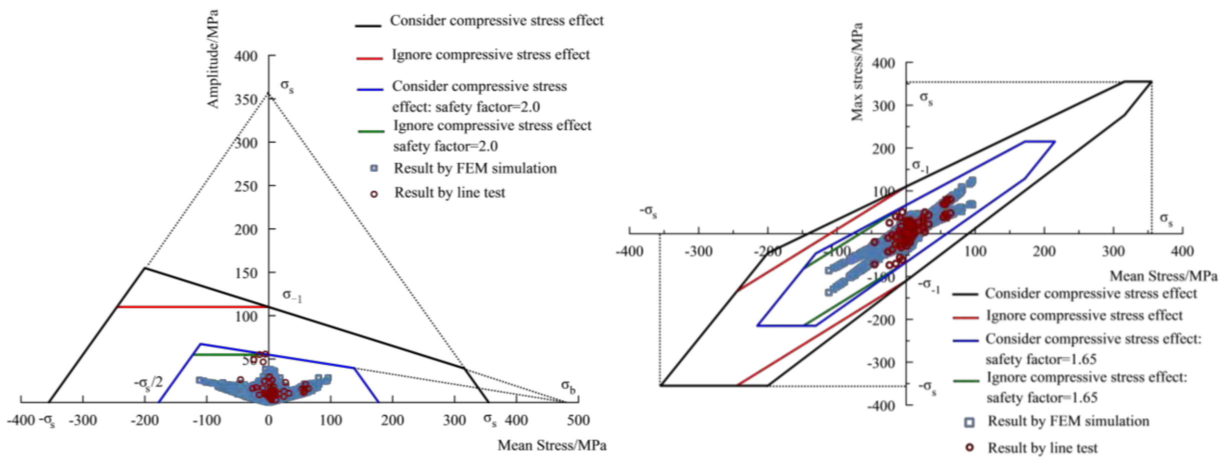
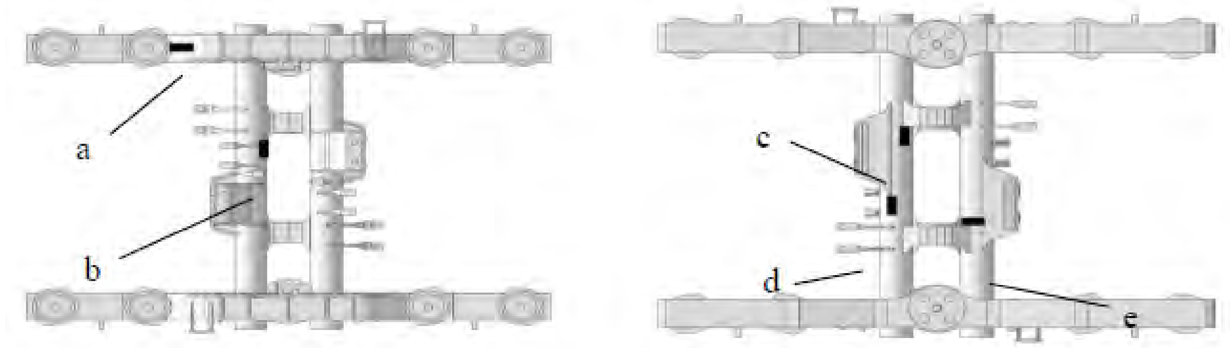


Fig. 6 Comparison between FEM Simulation and Line Test

From the results in Figure 5, the test results satisfy the Smith-Goodman diagram while slightly exceed the Haigh-Goodman envelope line, the reason of the difference is that the two evaluation methods adopt different safety factors.

From the comparison in Figure 6, the FEM simulation result is not conservative relative to line test. The big points are mainly locate in structure which bears transverse force, so the transverse load provided in norms are not conservative when used to evaluate the fatigue strength of subway vehicle.

By Cumulative Damage Approach



(a)Bottom side of bogie frame (b) Up side of bogie frame

Fig. 7 Test Points of Bogie Frame by Line Test

During the section, only 5 points are concerned, which are shown in Figure 7 and Figure 8, and the test result are shown in Figure 9. Before the evaluation, the fatigue limit σ-1 is needed, the fully reverse load fatigue limit is calculated by the formula in [15]

$$\sigma_{-1} = \mathrm{K}_{\mathrm{AK},\sigma} \cdot \mathrm{K}_{\mathrm{E},\sigma} \cdot \frac{92}{225/(\mathrm{FAT} \cdot \mathrm{f_t} \cdot \mathrm{K_V} \cdot \mathrm{K_{NL,E}})} \tag{10}$$

Where KAK, σ is the mean stress factor, equal to 1 because that the stress obtained are already modified by mean stress, KE, σ is the residual stress factor, equal to 1.26 becasue of moderate residual stress, FAT is fatiuge class, which are shown in Table 3, ft, Kv, KNL, E are thickness factor, surface treatment factor separately, they all equal to 1. So the fatigue limit are obtained shown in Table 3.

Tab. 3 Fatigue classes (FAT) of test points

Name	Test points of line test [MPa]				
	a	b	c	d	e
Mean stress	62.66	1.65	-24.5	-33.7	-15.3
FAT	71	90	90	90	71
σ_{-1}	36.58	46.37	46.37	46.37	36.58

The second important process is to correct the stress spectrum to fully reverse load spectrum consider mean stress. The correction formulas are

When $R_\sigma < 0$,

$$\sigma_{a,i,R_\sigma=-1} = \sigma_{a,i} \cdot \left(1 + M_\sigma \cdot \sigma_m / \sigma_a\right) \tag{11}$$

When $0 \le R\sigma < 0.5$,

$$\sigma_{a,i,R_\sigma=-1} = \sigma_{a,i} \cdot \frac{1 + \frac{M_\sigma}{3} \cdot \frac{\sigma_m}{\sigma_a}}{\frac{1 + M_\sigma / 3}{1 + M_\sigma}} \tag{12}$$

When $0.5 \le R\sigma < 1$,

$$\sigma_{a,i,R_\sigma=-1} = \sigma_{a,i} \cdot \frac{3\cdot(1+M_\sigma)^2}{3+M_\sigma} \tag{13}$$

When Rσ ⩾ 1,

$$\sigma_{a,i,R_\sigma=-1} = \sigma_{a,i} \cdot (1-M_\sigma) \tag{14}$$

Where Rσ = σmin/σmax.

Fig. 8 Test Points of Bogie Frame

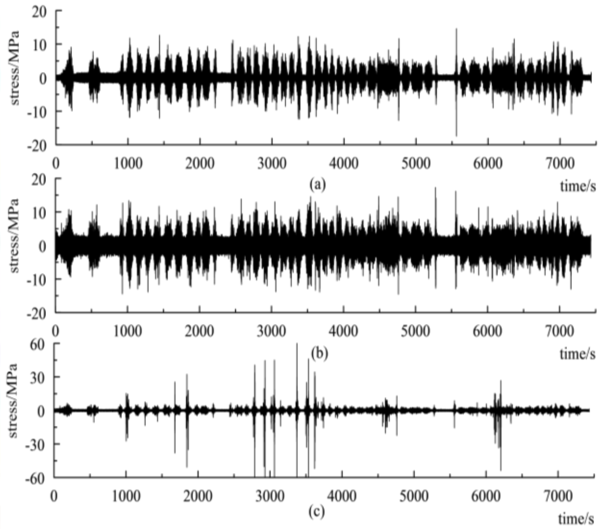


Fig. 9 the Line Test Stress Result

The corrected stress spectrums are shown in Figure 10 with S-N curve, which represent 30 years operation stress. The fatigue evaluation adopted is from reference [15]. During the calculation, the critical damage sum is 0.5, the safety factor is 1.35, and the slope k of the S-N curve is 3 when stress amplitude is greater than fatigue limit. The operation life of the bogie frame calculated by four S-N curve are given in Table 4.

From the results in Table 4, the conclusion is that the elementary S-N curve is too conservative to reflect the real operation environment; the result calculated by elementary S-N curve is not satisfied. Standard 1 curve and Standard 2 curve all exist infinite area during evaluation, which likes endurance limit approach. Sometimes, standard 1 and standard 2 could not give the intuitional fatigue strength. With regard to Haibach modified S-N curve, the results are approximate with that in standard 2 when stress spectrum has big stress level, and it also could give a quantitative result though the stress level is small.

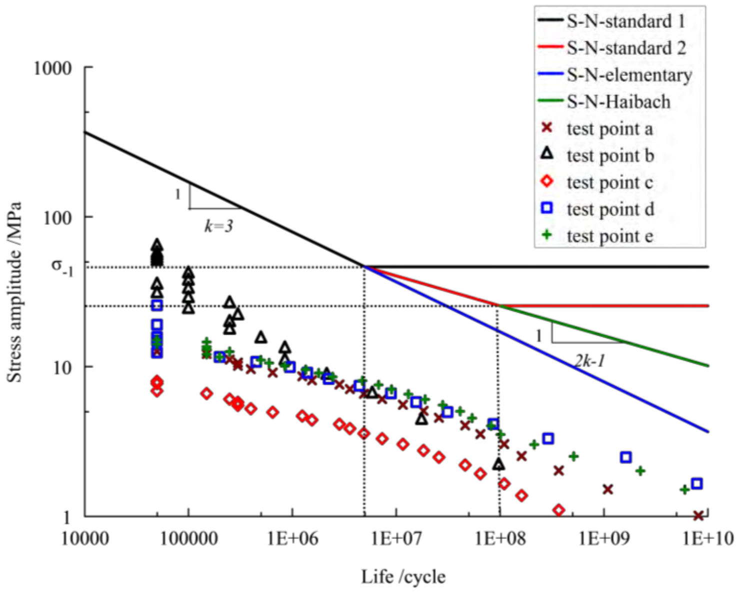


Fig. 10 the Stress Spectrum of Test Points by Line Test

Tab. 4 Fatigue Life of the Concerned Test Points

S-N curve	Test points of line test [year]				
	a	b	c	d	e
Standard 1	Infinite	51.8	Infinite	Infinite	Infinite
Standard 2	2571	43.4	Infinite	Infinite	Infinite
Elementary	8.8	34.2	69.1	30.6	126.9
Haibach	233	42.6	3557	1763	12851

Summary

The fatigue strength of a railway vehicle bogie frame is evaluated by endurance limit approach and cumulative damage approach. The differences between the two approaches are studied, and the conclusions are shown below.
(1) The Haigh-Goodman and Smith-Goodman diagram are identical when considering the same safety factor, while Haigh-Goodman provided in JIS standard is conservative relative to that in UIC standard due to adopting different safety factor.
(2) The transverse load recommended in UIC norm are not conservative when evaluate the fatigue strength of bogie frame.
(3) The elementary S-N curve are too conservative to reflect real situation, and the Haibach modified S-N curve are recommended when using cumulative damage approach because its advantage.

Acknowledgement

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