Fatigue Strength Evaluation of Welded Structure on Aluminum Alloy Car Body Based on Multi-Axial Stress

Yiming Shangguan
University of Science and Technology Beijing
Wenjing Wang (wjwang@bjtu.edu.cn)
Beijing Jiaotong University https://orcid.org/0000-0002-4136-5730
Chao Yang
BJTU: Beijing Jiaotong University
Anrui He
University of Science and Technology Beijing

Original Article

Keywords: Aluminum allay carbody, Fatigue strength assessment, Multi-axial stress, Welded joint

Posted Date: December 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1115402/v1

Title page

Fatigue Strength Evaluation of Welded Structure on Aluminum Alloy Car Body Based on Multi-axial Stress

Yiming Shangguan, born in 1996, is currently a PhD candidate at *National Engineering Technology Research Center of Flat Rolling Equipment, University of Science and Technology Beijing*. She received her bachelor degree from *University of Science and Technology Beijing* in 2020, meanwhile, she is researching in structural strength testing laboratory of *Beijing Jiaotong University, China*, as a research assistant. Her research interests include vehicle structure static strength and fatigue strength assessment.
E-mail: B20200529@xs.ustb.edu.cn

Wenjing Wang, born in 1976, is currently a professor at *School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, China*. She received her PhD degree from *Beijing Jiaotong University, China*, in 2004. Her research interests include rail vehicle structure strength and fatigue reliability theory and test.
Tel: +86-10-51683195; E-mail: wjwang@bjtu.edu.cn

Chao Yang, born in 1988, is currently a lecturer at *School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, China*. He received his PhD degree from *Southwest Jiaotong University, China* in 2012. His research interests include rail vehicle dynamics.
E-mail: ychao@bjtu.edu.cn

Anrui He, born in 1972, is currently a professor at *National Engineering Technology Research Center of Flat Rolling Equipment, University of Science and Technology Beijing*. He received his bachelor degree from *University of Science and Technology Beijing* in 1994. His research interests include virtual simulation and digital twins.
E-mail: harui@ustb.edu.cn

Corresponding author: WANG Wenjing E-mail: wjwang@bjtu.edu.cn

ORIGINAL ARTICLE

Fatigue Strength Evaluation of Welded Structure on Aluminum Alloy Car Body Based on Multi-axial Stress

Yi-Ming Shangguan [1,2] • Wen-Jing Wang [2] • Chao Yang [2] • Anrui He [1]

Received June xx, 201x; revised February xx, 201x; accepted March xx, 201x

Abstract: With the continuous development of the subway, the demand for its safety and stability is getting higher and higher. It is of great significance to accurately evaluate the fatigue life of the carbody to ensure the subway's safe operation. In this paper, the finite element model of a subway head carbody was established, and the fatigue strength of the welded structure on the carbody was evaluated based on Multi-axial stress. The local coordinate system was defined according to the geometrical characteristics of the welds. Local stresses perpendicular and parallel to the weld seam were obtained to calculate the stress ratio, stress range, and allowable stress value corresponding to the stress component. According to the joint fatigue resistance, the components of the degree of utilization and comprehensive degree of utilization are calculated to evaluate the structural fatigue strength under the survival rate of 97.5% and load cycles of 10^7. The evaluation of the fatigue strength of the pivotal weld joints shows that the fatigue strength of the aluminum alloy carbody meets the design requirements, the weld of the carbody has a strong ability to resist fatigue damage. The fatigue strength of the weld is mainly affected by the normal stress component, while the shear stress has little effect on the fatigue strength of the structure. In addition, compared with the filleted weld joint and the butt-welded joint, the normal stress parallels to and perpendicular to the weld direction and shear stress have the greatest effect on the lap-welded joint. Meanwhile, the comprehensive degree of utilization of the lap-welded joint is the largest at 0.49. The introduction of multi-axial stress for the fatigue strength evaluation is beneficial when considering the material utilization degree in multiple structural directions. This research results provide a reference for fatigue strength evaluation of subway carbody's welded structure.

✉ Wen-Jing Wang
wjwang@bjtu.edu.cn

1 National Engineering Technology Research Center of Flat Rolling Equipment, University of Science and Technology Beijing, Beijing 100083, China.
2 School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China.

Keywords: Aluminum allay carbody • Fatigue strength assessment • Multi-axial stress • Welded joint

1 Introduction

With the rapid development of urban rail transit, metro vehicles have become one of the first choices of urban transportation. The carbody is the main bearing structure of subway vehicles, which is located on the bogie and bears various dynamic and static loads during operation. Fatigue failure is one of the most critical failure modes of carbody structure, and the fatigue strength analysis of the carbody is of vital importance. Compared with carbon steel carbody, the aluminum alloy carbody has the advantages of lightweight, high corrosion resistance, excellent extrusion resistance and low overall cost. For aluminum alloy materials, the fatigue strength of the welded joint is about half of the base metal, and the base metal is not prone to fatigue failure compared with the welded joint. Therefore, the fatigue strength evaluation of the aluminum alloy carbody mainly focuses on welded joints.

Approaches for fatigue evaluation of welded structures include nominal stress method, hot spot stress method, effective notch stress method, structural stress method, etc. The nominal stress method[1–3] is widely used in the fatigue assessment of welded structures. It classifies the welded joint grades and directly estimates the fatigue strength of the structure according to the structural nominal stress and the S-N curve corresponding to different notch grades [4]. The failure criterion is to judge whether the nominal stress is less than the allowable nominal stress at fatigue fracture. The advantages of this method are that the solution process is simple, the mesh quality is not strictly required, and it is easy to obtain the nominal stress value. However, its evaluation process depends on the fatigue strength data of typical structural details. However, the joint types and loading modes in actual structures are complicated while the standards can only provide very limited reference. When confronted with welded components with complex weld shapes or forces, it is difficult to select the appropriate S-N curve, so it is difficult to define the nominal stress of welded structures with complex geometric shapes, nor to assess the fatigue strength of structures outside the specification [5].

In addition, when using finite element analysis, it is difficult to evaluate the accurate stress value at the stress concentration area, such as the weld root and weld toe due to the sensitivity of the stress to the mesh grids. In order to solve this problem, the hot spot stress method [6-7] is proposed. The hot spot stress is the structural stress at the hot spot, which is related to the overall geometry and load conditions of the welded structure but does not include the stress concentration caused by local factors such as weld size and welding defects. W J Wang et al. [8] used the hot spot stress method to calculate the hot spot stress value at the welding toe, and a modified S-N curve considering the thickness effect of the main board was proposed to predict the fatigue life of the sample.

B J Wang et al. [9] compared the hot spot stress calculation result with the nominal stress from shell elements in welded bogie frame, the result shows that hot spot stress is higher than the nominal stress. Z Y Zhou et al. [10] clarified the limitations of the hot spot stress method. He proposed that the hot spot stress method could effectively evaluate the failure of the toe based on the geometrical discontinuity of the welding structure but could not evaluate the fatigue failure caused by the defects in the weld root and inside the weld. This method is suitable for the fatigue analysis of the toe of non-standard structural details and complex welding joints.

The effective notch stress method [11-12] uses a specific radius to replace the notch at the weld root and toe and calculates the effective notch stress at the weld toe and weld root by finite element method, which avoids the occurrence of stress singular value at the sharp gap and can be used for fatigue evaluation at the weld root and toe. It can also determine whether fatigue failure occurs at the weld root or toe by principal stress. W Shen et al.[13] evaluated the fatigue strength of welded joints and the results show that the proposed method based on notch stress strength theory has the additional advantage in simplified fatigue strength estimation for welded joints and it is able to account for the thickness effect observed in welded joints. Y F Chang et al.[14] considered the effects of the alloy materials and joint size on the effective notch stress and proposed a virtual radius between 0.05 and 0.25 mm based on the FEM and the effective notch stress method. Xu Liu et al. [15-16] obtained the stress concentration coefficient of the welded joint gap by using the formula method and numerical method respectively and obtained an S-N curve with a lower slope than the FAT225 curve recommended by the International Welding Society (IIW).

At present, if the hot spot stress method or effective notch stress method is adopted in the analysis of vehicle body structure, the required grid division of weld area is exceedingly small, leading to an excessively large number of grids at the weld area. Meanwhile, it is very likely that an abrupt change of grid size in the transition area between large and small grids may happen, which is not appropriate in engineering [17].

Based on the basic principles of fracture mechanics, the structural stress method [18-19] unifies the fatigue S-N data of different joint forms, thicknesses and loading modes, and predicts the fatigue life of welded structures with a main S-N curve. This method is not sensitive to the grid and has high calculation accuracy, and the effects of stress concentration, plate thickness and load mode on fatigue life can be considered simultaneously [20-21]. S Z Zhou et al. [22] developed the weld fatigue life evaluation and visualization system for railway freight cars based on the structural stress method and 3d visualization method, which directly reflected the fatigue distribution of the weld with color cloud image and evaluated the weld fatigue life visually and efficiently. S M Xie [23] and X W Li et al. [24] used the structural stress method to predict the fatigue life of the welded structure of rail vehicles, but the calculation steps were complicated and the result data could not be directly mapped to each node in the weld model. The research on the fatigue assessment of railway vehicle carbody structures is still in progress [25–30], and there is ample space for improvement and development.

Massive studies have shown that welded structures exhibit significant multi-axial stress characteristics even under the action of a single load, and the use of uniaxial criterion to evaluate the fatigue strength of structures will have an important impact on the accuracy of the results. Plentiful welded joint design standards provide fatigue life assessment curves of various welded joints, which are derived from uniaxial loading tests. These fatigue life curves do not apply to multi-axial loading, so it is of great significance to solve the problem of fatigue life assessment of welded structures under multi-axial loading.

In this paper, the aluminum alloy subway head carbody produced by a locomotive factory is taken as the research object. The load condition is based on *EN 12663-1:2010 Railway Application -- Requirements for Railway Vehicle Body Structure* [31]. The fatigue evaluation method is based on the standard of *DVS 1608-2011 design and Strength Evaluation of Aluminum Alloy Welded Structures in Railway Vehicle Manufacturing* [32]. Various parameters of the carbody were simulated and analyzed, and the process of evaluating the fatigue life of the DVS1608 standard was programmed by APDL language, and the fatigue strength of the key weld parts of the aluminum alloy carbody was evaluated. The results show that the fatigue strength of the carbody meets the design requirements. The results verified the accuracy and applicability of the multi-axial stress assessment method for aluminum alloy carbody welded structures. This study provides a basis and reference for the application of the multi-axial stress to the fatigue assessment of welded structures in the aluminum alloy carbody.

2 Main Structure of the Head Carbody

The head carbody is a lightweight, monocoque cylindrical structure welded from large-section aluminum profiles and plates. It is designed mainly to carry all the equipment and personnel of the vehicle and provide installation interfaces for the vehicle equipment. It is mainly composed of large components, such as the underframe, sidewalls, end walls, and roof. The roof, sidewalls, end walls, and underframe are welded when assembling the aluminum alloy carbody. There are three welding forms of butt welding, fillet welding and lap welding. Typical weld structures of the carbody are shown in Figure 1. Table 1 lists the basic mechanical properties and allowable stresses of materials in each part of the head carbody.

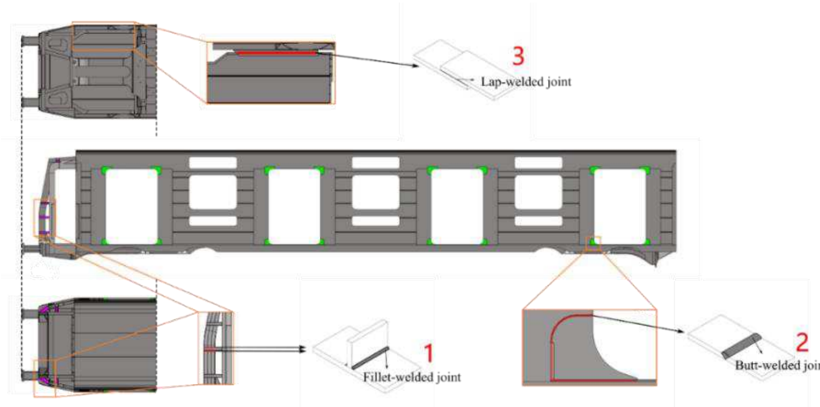


Figure 1 Schematic diagram of weld structure of head carbody

Table 1 Mechanical Properties of Materials

SN	Type	Material	Components	Thickness t (mm)	Strength limit (MPa)	Yield strength (MPa)	
						Base metal	Weld
1	Plate	5083-H111	Hatch cover end plate, partial cavity sealing plate	$t \le 50$	275	125	125
				$50 < t \le 80$	270	115	115
2	Section	6005-T6	Main structure of the carbody	$t \le 5$	255	215	115
				$5 < t \le 10$	250	200	115
3	Section	6082-T6	Profile of draft sill, sleeper beam and bumper beam	$t \le 5$	290	250	125
				$5 < t \le 15$	310	260	125
4	Plate	6082-T6/T651	Cab connecting plate, partial plate of draft sill, sleeper beam and bumper beam	$t \le 6$	310	260	125
				$6 < t \le 12.5$	300	255	125
		6082- T651		$12.5 < t \le 100$	295	240	125
	Forged alloy	6082- T6	Door corner	$t \le 100$	290	250	125

3 Fatigue Strength Analysis

3.1 Fatigue Strength Assessment for Weld

The stress component needs to be evaluated at the weld position, which refers to the axial force parallel to and perpendicular to the weld direction (σ_{II} and $\sigma_{\perp}$) and the shear stress (τ) parallel to the weld direction, shown as Figure 2.

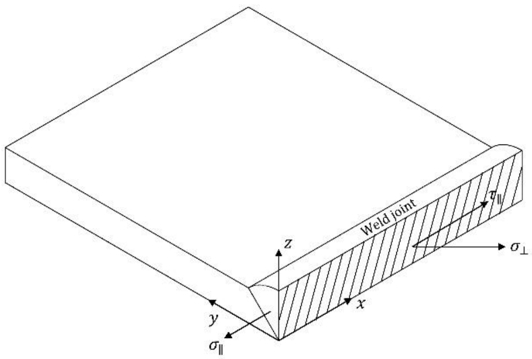


Figure 2 Three stress components at the weld area

The stress components of the node in the global coordinate system include normal stress components $\sigma_x, \sigma_y, \sigma_z$ and shear stress components $\tau_{xy}, \tau_{yz}, \tau_{xz}$. The transformation formula of node stress components in different coordinate systems is as follows:

$$\sigma_{j'k'} = \alpha_{j'j}\alpha_{k'k}\sigma_{jk} \quad (1.)$$

$$\sigma_{j'} = \alpha_{j'1}^{2}\sigma_1 + \alpha_{j'2}^{2}\sigma_2 + \alpha_{j'3}^{2}\sigma_3 \quad (2.)$$

Where,

σ_{jk} is the second-order tensor in the global coordinate system;

$\sigma_{j'k'}$ is the second-order tensor in the local coordinate system;

$\alpha_{j'j}$, $\alpha_{k'k}$ are the cosine of the included angle of the corresponding axes of two coordinate systems;

$\sigma_1, \sigma_2, \sigma_3$ are the principal stress.

3.2 Assessment Criteria

The normal stress and corresponding shear stress in the local coordinate system at the key position of the weld are extracted. Then the normal stresses ($\sigma_{\perp}$ and $\sigma_{\parallel}$) and the relative shear stress τ in the local coordinate system are evaluated. Fatigue calculation must be carried out for each stress component:

$$a_{\perp} = \left|\frac{\sigma_{\perp}}{[\sigma_{\perp}]}\right| \leq 1 \quad (3.)$$

$$a_{\parallel} = \left|\frac{\sigma_{\parallel}}{[\sigma_{\parallel}]}\right| \leq 1 \quad (4.)$$

$$a_{\tau} = \left|\frac{\tau}{[\tau]}\right| \leq 1 \quad (5.)$$

Where,

$a_{\perp}$ is the utilization degree under normal stress in the x-direction of local coordinates;

$a_{\parallel}$ is the utilization degree under normal stress in the y-direction of local coordinates;

a_{τ} is utilization degree under shear stress;

$[\sigma_{\perp}], [\sigma_{\parallel}], [\tau]$ are allowable fatigue strength values, and the above utilization degrees ($a_{\perp}$、$a_{\parallel}$、a_{τ}) must be less than or equal to 1.

In addition, the influence of multiaxial stress must be considered, which satisfies the following equation (6):

$$\alpha_v = \sqrt{(a_{\perp})^2 + (a_{\parallel})^2 + f_v \cdot (a_{\perp}) \cdot (a_{\parallel}) + (a_{\tau})^2} \leq 1 \quad (6.)$$

Where, f_v is the phase effect of $\sigma_{\perp}$ and $\sigma_{\parallel}$ ranging from -1.0 to +1.0; and the conservative value is 1.0. α_v is the comprehensive degree of utilization.

3.3 Calculation of Allowable Fatigue Strength

The fatigue strength of the welding site is independent of the base metal alloy and only depends on the stress ratio R_{σ} and R_{τ}. The notch condition curve coefficient x is given in Appendix B of DVS1608. M_{σ} and M_{τ} are the moderate stress sensitivity coefficients of normal stress and shear stress, respectively. Where $M_{\sigma} = 0.15, M_{\tau} = 0.09$. If there is residual stress in the transition zone of the weld to the base metal, a surplus coefficient can be applied to the fatigue strength. The interference coefficient of low internal stress is obtained by increasing M_{σ} to 0.3 and M_{τ} to 0.17, when $R_{\sigma} \geq 0.5$ or $\tau \geq 0.5$ is applicable. The allowable amplitude of fatigue strength of normal stress is obtained from equation (7)-(10):

Interval 1：$R_{\sigma} > 1$

$$[\sigma_{(R)}] = 54 \cdot 1.04^{-x} \leq 1 \quad (7.)$$

Interval 2：$R_{\sigma} \leq 0$

$$[\sigma_{(R)}] = 46 \cdot 1.04^{-x}\left(\frac{1}{1 + M_{\sigma}\frac{1 + R_{\sigma}}{1 - R_{\sigma}}}\right) \quad (8.)$$

Interval 3：$0 < R_{\sigma} < 0.5$

$$[\sigma_{(R)}] = 42 \cdot 1.04^{-x}\left(\frac{1}{1+\frac{M_\sigma}{3}\frac{1+R_\sigma}{1-R_\sigma}}\right) \tag{9.}$$

Interval 4：$0.5 \le R_\sigma < 1$

$$[\sigma_{(R)}] = 36.5 \cdot 1.04^{-x} \tag{10.}$$

The allowable amplitude of fatigue strength of shear stress $[\tau]$ is obtained from equation (11)-(13).

Interval 2：$-1 \le R_\tau \le 0$

$$[\tau_{(R)}] = 28 \cdot 1.04^{-x}\left(\frac{1}{1+M_\sigma\frac{1+R_\sigma}{1-R_\sigma}}\right) \tag{11.}$$

Interval 3：$0 < R_\tau < 0.5$

$$[\tau_{(R)}] = 26.5 \cdot 1.04^{-x}\left(\frac{1}{1+\frac{M_\sigma}{3}\frac{1+R_\sigma}{1-R_\sigma}}\right) \tag{12.}$$

Interval 4：$R_\tau > 0.5$

$$[\tau_{(R)}] = 24.4 \cdot 1.04^{-x} \tag{13.}$$

4 Fatigue Strength Evaluation of the Welded Structure of Carbody

4.1 Calculation Case for Fatigue Strength

According to *EN 12663-2010 Railway Applications — Structural Requirements of Railway Vehicle Bodies*, the calculated fatigue strength load of the carbody is determined. ±0.15g is the acceleration amplitude, and the stress has little influence on the fatigue life, while the stress amplitude is the key to affecting the fatigue life, so 0.15g acceleration is applied on the carbody. The calculated loads were divided into three types. Combined with the actual operation of the vehicle, all 28 weld fatigue load conditions were obtained by extending the load types according to the three types of load conditions.

Table 2 List of Load Cases for Fatigue Strength Assessment and Calculation

Load	*Acceleration* /(m/s²)			*Additional load*
	X	Y	Z	
1	±0.15g	0.0	1g	Lateral wind load，Sw=200N/ m²
2	0.0	±0.15g	1g	
3	0.0	0.0	1±0.15g	
4	±0.15g	±0.15g	1±0.15g	
5	±0.15g	0.0	1g	Line twisting load
6	0.0	±0.15g	1g	
7	0.0	0.0	1±0.15g	
8	±0.15g	±0.15g	1±0.15g	

4.2 Steps for weld Fatigue Strength Assessment

According to *DVS1608-2011 Design and Strength Assessment of Welded Structures from Aluminum Alloys in Railway Applications*, the fatigue strength of carbody structure was evaluated. Based on the DVS1608 standard, the fatigue strength evaluation method is programmed by APDL language and ANSYS as a secondary development platform. The weld fatigue assessment flow in the standard is shown in Figure 3.

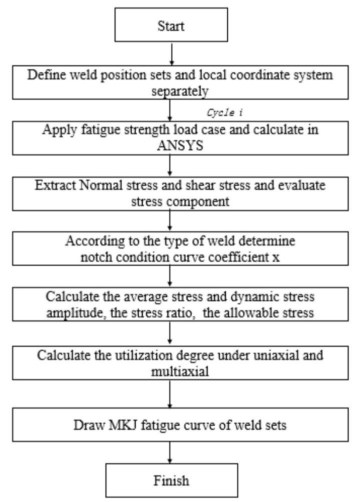


Figure 3 Flow chart of fatigue life evaluation based on DVS1608 standard

4.3 Node Set Naming Rules for Fatigue Assessment

The Node group ID of the fatigue assessment Node set ranges from 101 to 999 by default. The node group name is:

name1_ name2_ CXYZ

Where, name1 is the name of the component to which the node belongs, such as Underframe or Sidewall. Name2 is the type of weld to which the node belongs. CXYZ is the name of the local coordinate system. C is shorthand for the coordinate system.

X represents the direction along the weld, and the value range is [0, 1, 2, 3, 9]. 0 represents the global coordinate system. 1 represents the X-axis of the global coordinate system; 2 represents the Y-axis of the global coordinate system; 3 represents the Z-axis of the global coordinate system; 9 represents the axis of the local coordinate system.

Y represents the perpendicular direction of the weld, and its value range is [0, 1, 2, 3, 9]. The numerical significance is the same as above. Z represents the normal direction of the weld, which is in accordance with the right-hand screw rule with X and Y.

When the three directions above coincide with the global coordinate system (not necessarily in the same order), CXYZ is named C000; When only the weld direction overlaps with the global coordinate system X-axis, CXYZ is named C199; CXYZ is named C919 when only the perpendicular direction of the weld line rematches the x-axis of the global coordinate system. When only the normal direction of the weld plane overlaps with the x-axis of the global coordinate system, CXYZ is named C991. The rest set names can be done in the same manner.

When evaluating the fatigue strength in the ANSYS platform, the stress in the overall Cartesian coordinate system should be converted to the local coordinate system for evaluation. In addition, the program cannot directly identify the node being evaluated. Therefore, the sets of welded locations corresponding to the local coordinate system need to be established one-to-one during modeling. The program evaluates the nodes in the set according to the direction of the local coordinate system. The assessed position of each weld is marked with white points in the finite element diagram, and the two rows of nodes with a distance of 5mm from the weld are taken as evaluation points. Besides, the length of the strain gauge is ignored, so the calculated results are conservative. The specific information of the local coordinate system and evaluation nodes is shown in Figure 4.

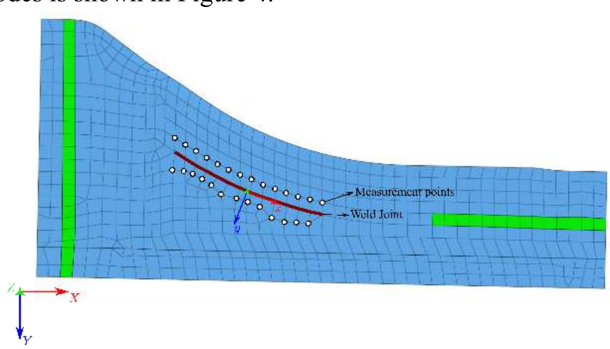


Figure 4 Underframe_butt-welded joint_c992

4.3 Fatigue Characteristic Curve

The MKJ (Moore-Kommers-Japer) fatigue characteristic curve of aluminum alloy is drawn according to different notch curve indexes. Figure 5 present the MKJ diagrams of normal stress and shear stress of different aluminum alloy welded joints under the survival rate of 97.5% and load cycles of 1×10^7. The calculation results of key welds should be within the fatigue strength curve of the MKJ diagram shown in the figure.

In the MKJ fatigue curve, the horizontal axis is the stress ratio R, and the vertical axis is the maximum allowable stress corresponding to the stress ratio.

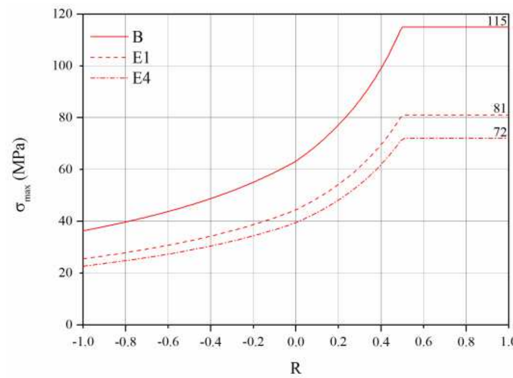


Figure 5 MKJ fatigue curve with average stress $\sigma_m \geq 0$

5 Critical Parts of Fatigue Analysis Results

According to DVS1608 standard, weld 1 belongs to the fillet-welded joint, thus the E4 notch curve for normal stress and the H notch curve for shear stress is adopted. Weld 2 belongs to butt weld and is welded through on one side. Hence the E1 notch curve is selected for normal stress, and the G notch curve is selected for shear stress. Weld 3 belongs to the Lap-welded joint, therefore, the F2 notch curve is chosen for normal stress, and the H notch curve is chosen for the shear stress. The plate thickness at positions 1, 2 and 3 of the welds is less than 10mm, and the influence of the plate thickness is not considered, so there is no need to modify the allowable stress.

The overall structural stress on the carbody model under 28 operating load cases is calculated using ANSYS software. Then read all the normal stresses of each condition in the X- and Y-directions under the global coordinate system together with the normal and shear stresses along with and perpendicular to the weld direction.

Calculate the average stress and dynamic stress amplitude, the stress ratio, the allowable stress. Finally, the fatigue strength utilization of the material is calculated to determine whether the fatigue strength of the weld meets the design requirements. Table 3 to Table 5 lists the stress ratio of normal stress, shear stress and allowable stress of all weld positions under various loading conditions. Table 6 lists the weld fatigue strength evaluation results.

Explanation of notations in the following tables:

σ_{m}: mean value of normal stress, σ_{a}: normal stress amplitude; σ_{min}: minimum normal stress; σ_{max}: maximum normal stress.

R: stress ratio of minimum stress to maximum stress; 1/R: the inverse of the stress ratio.

τ_{m}: mean value of shear stress; τ_{a}: shear stress amplitude; τ_{min}: minimum shear stress; τ_{max}: maximum shear stress.

Table 3 Calculation of Stress Ratio and Allowable Stress for Normal Stress ($\sigma_\perp$) in Vertical Direction at Various Weld Positions (MPa)

Weld position	σ_m	σ_a	σ_{min}	σ_{max}	R	$\frac{1}{R}$	$M\sigma$	$[a_\perp]$
Fillet-welded joint 1	5.50	1.26	4.24	6.76	0.63	1.59	0.3	18.02
Butt-welded joint 2	19.01	3.29	15.72	22.31	0.70	1.42	0.3	20.27
Lap-welded joint 3	10.02	2.29	7.73	12.31	0.63	1.59	0.3	7.31

Table 4 Calculation of Stress Ratio and Allowable Stress for Normal Stress ($\sigma_\perp$) along the Weld Direction at Various Weld Positions (MPa)

Weld position	σ_m	σ_a	σ_{min}	σ_{max}	R	$\frac{1}{R}$	$M\sigma$	$[a_\parallel]$
Fillet-welded joint 1	-8.15	2.22	-10.37	-5.93	1.75	0.57	0.3	26.65
Butt-welded joint 2	-22.49	3.90	-26.39	-18.59	1.42	0.70	0.3	29.98
Lap-welded joint 3	-9.98	2.23	-12.21	-7.76	1.57	0.64	0.3	10.82

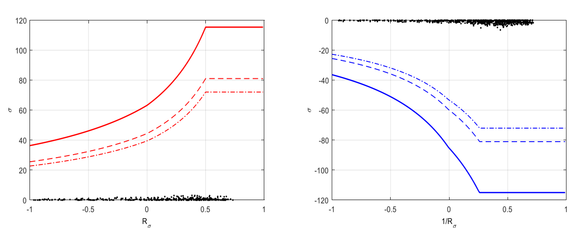
Table 5 Calculation of Stress Ratio and Allowable Stress for Shear Stress (τ) at Various Weld Positions (MPa)

Weld position	τ_m	τ_a	τ_{min}	τ_{max}	R	$\frac{1}{R}$	$M\tau$	$[a_\tau]$
Fillet-welded joint 1	2.88	0.72	2.15	3.60	0.60	1.67	0.17	11.14
Butt-welded joint 2	5.84	1.03	4.82	6.87	0.70	1.43	0.17	8.14
Lap-welded joint 3	7.55	1.63	5.93	9.18	0.65	1.55	0.17	8.14

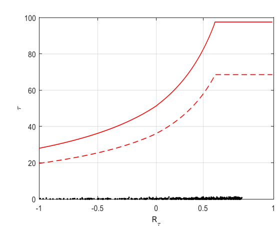
Table 6 Assessment Results of Fatigue Strength at Various Weld Positions (MPa)

Weld position	Normal stress in X-direction			Normal stress in Y-direction			Shear stress			α_v	Assessment
	σ_a	$\sigma_{a,zul}$	$a_\perp$	σ_a	$\sigma_{a,zul}$	$a_\parallel$	τ_a	$\tau_{a,zul}$	a_τ		
Fillet-welded joint 1	1.26	18.02	0.07	2.22	26.65	0.08	0.72	11.14	0.06	0.15	Pass
Butt-welded joint 2	3.29	20.27	0.16	3.90	29.98	0.13	1.03	8.14	0.12	0.28	Pass
Lap-welded joint 3	2.29	7.31	0.31	0.25	10.82	0.21	1.63	8.14	0.20	0.49	Pass

The maximum and minimum normal stresses were obtained by plane stress calculation and the allowable stresses of corresponding components were obtained by the evaluation process. After data processing, the calculated results of the directional stress of the weld are drawn in the MKJ fatigue characteristic curve of the corresponding welded joint. MKJ fatigue strength curves of weld seams with three different welding forms are shown in Figure 6 to Figure 8.

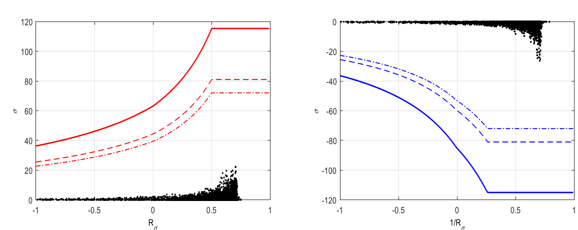


(a) $\sigma_m > 0$　　（b） $\sigma_m < 0$

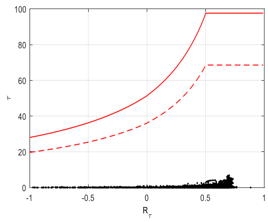


(c)Shear Stress

Figure 6 MKJ fatigue characteristic curve at Weld Position 1 in Driver's Cab

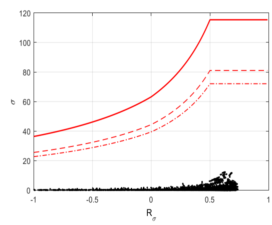


(a) $\sigma_m > 0$　　（b） $\sigma_m < 0$

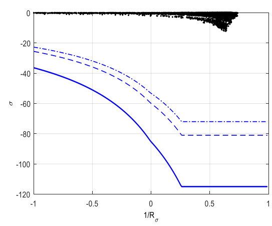


(c)Shear Stress

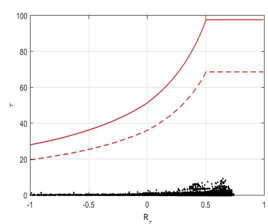
Figure 7 MKJ fatigue characteristic curve at Weld Position 2 in Sidewall



(a) $\sigma_m > 0$



（b） $\sigma_m < 0$



(c)Shear Stress

Figure 8 MKJ fatigue characteristic curve at Weld Position 3 in Underframe Area

According to the MKJ fatigue evaluation curve, it can be found that the normal stress and shear stress have a certain influence on the fatigue life of three welded joints. Table 6 illustrates the normal stress parallel to the direction of the weld has a greater influence on the three welded joints. The main factors affecting the fatigue life of the butt weld are the normal stress perpendicular to the direction of the weld. The main factors affecting the fatigue life of the lap-welded joint are the normal stress along the direction of the weld. The normal stress perpendicular to the weld and shear stress has less influence. In addition, the lap-welded joint has the highest comprehensive degree of utilization of 0.49. As shown in Figure 6 to Figure 8, the normal stress and shear stress of welded seam of the carbody structure are both within the MKJ fatigue evaluation curve, and the fatigue performance of welded seam of the carbody structure meets the standard requirements.

6 Conclusions

In this paper, the fatigue strength of welded structure on aluminum alloy carbody is evaluated based on multi-axial stress, the main conclusions are as follows:

(1) The components of the degree of utilization and comprehensive degree of utilization of the pivotal weld joints in the aluminum alloy carbody are less than 1, and there was no hidden danger of fatigue failure. The results show that the fatigue strength of the weld seams meets the design requirements under the survival rate of 97.5% and load cycles of 10^7.

(2) The orthogonal experiment design method is employed for the optimal design. As a result, a larger workspace of ZJUESA is obtained. For the three welds mentioned above, the normal stress parallel and perpendicular to the weld direction and shear stress have the greatest effect on the lap-welded joint compared with the fillet-welded joint and butt-welded joint. In addition, the comprehensive degree of utilization of the lap-welded joint is the largest (0.49). The fatigue strength of the weld is mainly affected by the normal stress component, while the shear stress has little effect on the fatigue strength of the structure. Through the evaluation process, it is found that the fatigue strength of welded structures can be improved in the following ways:

a. Change welding type and improve notch line grade to increase fatigue allowable stress. For instance, change lap-welded joint to fillet-welded joint; change partial penetration to full penetration; change single-sided welding to double-sided welding, etc.

b. Optimize the structure to reduce the stress range of welded joints. Improve notch line grade through weld processing technics, such as weld grinding.

(3) This paper used APDL language to program the process of DVS1608 standard fatigue life evaluation, and the multi-axial stress is investigated. This evaluation is more concise in form since it does not account for the use of the welded structure, and its focus is not on the calculation of service life but the fatigue strength of the structure. There are only two conclusions "qualified" and "unqualified", designers can determine the safety margin of the structure by comparing the utilization degree with 1, and the results are more targeted. This study can be used to evaluate the welding seam easily and quickly, which provides certain guidance and theoretical basis for fatigue evaluation of subway carbody’s welded structure.

7 Declaration

Acknowledgements
Not applicable

Funding
Supported by National Natural Science Foundation of China (No.52075032) and Science and Technology Research and Development Program of China State Railway Group Co., Ltd (No.P2021J006).

Availability of data and materials
The datasets supporting the conclusions of this article are included within the article.

Authors' contributions
The author' contributions are as follows: Wenjing Wang was in charge of the whole trial. Yiming Shangguan carried out the simulation and wrote the manuscript. Chao Yang performed the data processing and assisted with the theoretical analysis. Anrui He assisted with the theoretical analysis. All authors read and approved the final manuscript.

Competing interests
The authors declare no competing financial interests.

Consent for publication
Not applicable

Ethics approval and consent to participate
Not applicable

References

[1] ZAMZAMI I A, SUSMEL L. On the accuracy of nominal, structural, and local stress based approaches in designing aluminium welded joints against fatigue. *International Journal of Fatigue*, 2017, 101:137-158.

[2] F Guo, S Wu, J Liu, et al. Ding. A time-domain stepwise fatigue assessment to bridge small-scale fracture mechanics with large-scale system dynamics for high-speed maglev lightweight bogies. *Engineering Fracture Mechanics*. 2021, 248, 107711.

[3] Y N Hu, S C Wu , P J Withers, et al. Corrosion fatigue life assessment of high-speed railway EA4T steel with artificial scratches. *Engineering Fracture Mechanics*, 2021, 107588.

[4] Institution B S. Eurocode 9 Design of aluminium structures[S].British Standards Institution, 2007.

[5] L Yang, B Yang, G X Yang, et al. Overview of fatigue research of spot welded joints. *Journal of Mechanical Engineering*. 2020, 56:26. (in Chinese)

[6] B Karabulut, B Rossi, On the applicability of the hot spot stress method to high strength duplex and carbon steel welded details, *Engineering Failure Analysis*, 2021,128, 105629.

[7] A F Hobbacher, The new IIW recommendations for fatigue assessment of welded joints and components – A comprehensive code recently updated, *International Journal of Fatigue*, 2009, 31.

[8] W J Wang, J Y Bai, W Liu, Fatigue assessment of weld structure based on the hot spot stress method. *Journal of Beijing Jiaotong University*, 2017. (in Chinese)

[9] B J Wang, Q Li, and Z M Liu, Research on the stress fatigue assessment about the hot spot stress on the bogie frame. *Advanced Materials Research*, 2011,328-330:1281-1286. (in Chinese)

[10]Z Y Zhou, F LI, Study on fatigue analysis of welded toes of plate structures using hot spot stress method based on surface extrapolation. *Journal of the China Railway Society*, 2009, 31. (in Chinese)

[11] Mei JF et al. An overview and comparative assessment of approaches to multi-axial fatigue of welded components in codes and standards. *International Journal of Fatigue*, 2021, 146:106144.

[12] W Park, C Miki. Fatigue assessment of large-size welded joints based on the effective notch stress approach. *International Journal of Fatigue*, 2008, 30:1556-1568.

[13] W Shen, R J YAN , N Barltrop, et al. A method of determining structural stress for fatigue strength evaluation of welded joints based on notch stress strength theory[J]. *International Journal of Fatigue*, 2016:87-98.

[14] Y F Chang, C J Sun, Y Qiu. Effective notch stress method for fatigue assessment of sheet alloy material and bi-material welded joints[J]. *Thin-Walled Structures*, 2020, 151:106745.

[15] X Liu, K Zhang, B Liu, et al. The multi-axle fatigue analysis of welded joints based on notch stress method[J]. *Journal of Chongqing University*, 2017, 40, 9-17. (in Chinese)

[16] X Liu, C Zhou, K Zhang, et al. Fatigue performance analysis of bogie welded joints based on notch stress method[J]. *Journal of the China Railway Society*, 2017.

[17] H W Zhao, Simulation research on fatigue strength of railway passenger car body. *Rolling Stock*, 2021,59:11-15. (in Chinese)

[18] K Bao, Q Zhang, Y Liu, et al, Fatigue life of the welding seam of a tracked vehicle body structure evaluated using the structural stress method, *Engineering Failure Analysis*, 2021, 120, 105102.

[19] Z Z Wei, X J Pei, H Jin,Evaluation of welded cast steel joint fatigue data using structural stress methods, *Journal of Constructional Steel Research*, 2021, 186, 106895.

[20] G Meneghetti, A Campagnolo, D Rigon, Multiaxial fatigue strength assessment of welded joints using the Peak Stress Method – Part II: Application to structural steel joints, *International Journal of Fatigue*,2017, 101: 343-362.

[21] J K Hong, T P Forte, Fatigue Evaluation Procedures for Bi-axial Loaded Plate Joints Using the Battelle Structural Stress Method, Procedia Engineering, 2015, 133.

[22] S Z Zhou, Z L Zeng, C G Nie, et al. Research on fatigue life assessment and visualization of welds based on structural stress method. *Journal of Dalian Jiaotong University*,2018. (in Chinese)

[23] S M Xie, X K Zhou, X W Li, et al. Fatigue life prediction for weld line in heavy freight carbody based on ASME standard. *Chinese Journal of Computational Mechanics*, 2012,29:129-134. (in Chinese)

[24] X W Li, Development and key technologies of welded structure fatigue life prediction system based on master S-N curve method. *Computer Aided Engineering*, 2014.(in Chinese)

[25] B R Miao, Y X Luo, Q M Peng, et al. Multidisciplinary design optimization of lightweight carbody for fatigue assessment, *Materials & Design*,2020,194, 108910.

[26] Y Lu, L Dang, X Zhang, et al. Analysis of the dynamic response and fatigue reliability of a full-scale carbody of a high-speed train.

Journal of Rail and Rapid Transit, 2018, 232:2006-2023.

[27] H K Jun, H S Jung, D H Lee, et al. Fatigue crack evaluation on the underframe of EMU carbody[J]. *Procedia Engineering*, 2010, 2, 893-900.

[28] F Li, H Wu, C Liu, et al. Vibration fatigue analysis of high-speed railway vehicle carbody under shaking condition[J]. *Vehicle System Dynamics*, 2021.

[29] Y H Lu, H Y Zheng, J Zeng, et al. Fatigue life reliability evaluation in a high-speed train bogie frame using accelerated life and numerical test, *Reliability Engineering & System Safety*, 2019, 188, 221-232.

[30] Y Lu, HY Zheng, C Lu, et al. Analysis methods of the dynamic structural stress in a full-scale welded carbody for high-speed trains. Advances in Mechanical Engineering, 2018, 10.

[31] EN 12663-1:2010 Railway applications-structural requirements of railway vehicle bodies[S].

[32] D Gmbh. DVS 1608-2011 design and Strength Evaluation of Aluminum Alloy Welded Structures in Railway Vehicle Manufacturing [S].

Biographical notes

Yiming Shangguan, born in 1996, is currently a PhD candidate at *National Engineering Technology Research Center of Flat Rolling Equipment, University of Science and Technology Beijing*. She received her bachelor degree from *University of Science and Technology Beijing* in 2020, meanwhile, she is researching in structural strength testing laboratory of *Beijing Jiaotong University, China*, as a research assistant. Her research interests include vehicle structure static strength and fatigue strength assessment.
E-mail: B20200529@xs.ustb.edu.cn

Wenjing Wang, born in 1976, is currently a professor at *School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, China*. She received her PhD degree from *Beijing Jiaotong University, China*, in 2004. Her research interests include rail vehicle structure strength and fatigue reliability theory and test.
Tel: +86-10-51683195; E-mail: wjwang@bjtu.edu.cn

Chao Yang, born in 1988, is currently a lecturer at *School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, China*. He received his PhD degree from *Southwest Jiaotong University, China* in 2012. His research interests include rail vehicle dynamics.
E-mail: ychao@bjtu.edu.cn

Anrui He, born in 1972, is currently a professor at *National Engineering Technology Research Center of Flat Rolling Equipment, University of Science and Technology Beijing*. He received his bachelor degree from *University of Science and Technology Beijing* in 1994. His research interests include virtual simulation and digital twins.
E-mail: harui@ustb.edu.cn