Fatigue Strength Research on Aluminum Alloy Car Body for Railway Vehicle Based on Finite Element Analysis Method

Ning XIE[1,a], Yao-Hui LU[1,b,*], Zhen FENG[1,c], Tian-Li CHEN[2,d]

[1]School of Mechanical Engineering, Southwest Jiaotong University, Chengdu, Sichuan, China

[2]State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu, Sichuan, China

[a]xiening123@126.com, [b]yhlu2000@swjtu.edu.cn, [c]fengzhenok@163.com,
[d]tlchen@home.swjtu.edu.cn

*Corresponding author

Keywords: Aluminum Alloy Car body, Finite Element Analysis, Strength and Stiffness, Fatigue Strength.

Abstract. As the aluminum alloy car body was used to the lightweight design of railway vehicle, the fatigue reliability has become a key issue. In order to analyze the fatigue strength of aluminum alloy car body, the Goodman fatigue limit diagram was drawn according to the mechanical characteristics of aluminum alloy. The car body finite element model was established. The static strength and fatigue strength analysis load cases of car body were determined based on the *EN 12663* standard. After calculating and preparing post-processing analysis program, the car body fatigue strength was evaluated. The results show that under the static strength load cases, the maximum equivalent stress of car body which appears in the corner of the door is 225.481MPa and the maximum vertical deformation of car body is 6.87mm, both of them meet the static strength and stiffness requirements; Under the fatigue load cases, the minimum safety factor of car body fatigue strength is 2.41,which meets the fatigue strength requirement. The fatigue strength analysis method of aluminum alloy car body provides the reference data for lightweight design of car body.

Introduction

The lightweight of railway vehicles has become a trend in vehicle design because it can achieve the purposes of improving vehicle dynamic performance and energy-saving[1]. The use of aluminum alloy material can achieve the large wide-body of profile for its light weight, high strength and other characteristics. Aluminum alloy material get a lot of applications in railway vehicles and become a hot research in today's world[2]. But using aluminum alloy material bring a key issue of car body fatigue strength evaluation. Domestic and foreign scholars have launched research on the fatigue strength of car body. Yaohui Lu etc. analyzed the aluminum alloy car body fatigue strength influenced by aerodynamic loads[3]; Seo introduced the necessity of evaluating aluminum alloy car body fatigue strength with a large dynamic load test method[4]. This paper drawn the car body material's Goodman curve according to the mechanical properties parameters of aluminum alloy and used standard <*EN12663:Railway applications-structural requirements of railway vehicle bodies*>(abbreviate as *EN12663*). Then the aluminum alloy car body fatigue strength was evaluated after FEM calculation.

Goodman Curves of Aluminum Alloy for Evaluation Fatigue Strength

Mechanical Properties of Aluminum Alloy Material

A7N01 aluminum alloy has been widely used in structural materials of train tracks. It's a strong weldable alloy of Al-Zn-Mg series. A7N01 aluminum alloy is an ideal medium-strength structural welding materials for its superior weldability and weld quality. But A7N01 welded joints also have

Shortcomings as stress corrosion cracking, corrosion fatigue and so on. The basic properties parameters of the base metal and weld are shown in Tab.1.

Tab.1 Car body material properties

	Ultimate Strength σ_b (Mpa)	Yield Strength σ_s (MPa)	Fatigue limit σ_{-1} (Mpa)	Elastic Modulus E(GPa)	Poisson's ratio	Density ρ (kg/m^3)
Base metal	430	295	102	70	0.3	2700
Weld	247	128	90	70	0.3	2700

Drawing of Goodman Curve

Goodman fatigue curve is the basis for evaluation of fatigue strength provided in standard < *Interim provisions of strength design of railway vehicles above 200km/h speed level and identification test*>(abbreviate as *Interim Provisions*). The Goodman curve is easy to draw through simple geometric construction. The key is to get the ultimate strength σ_b, yield limit σ_s andfatigue limit σ_{-1} under cyclic symmetry conditions. The Goodman fatigue limit diagram as Fig.1 is drawn based on Tab.1. Among them, σ_m is mean stress, σ is the maximum (minimum) principal stress and points A to H are stress feature points. The aluminum alloy Goodman curve is a fatigue failure envelop curve. After N times loading cycles, the mark of structure fatigue failure is that the stress points fall outside the closed curve.

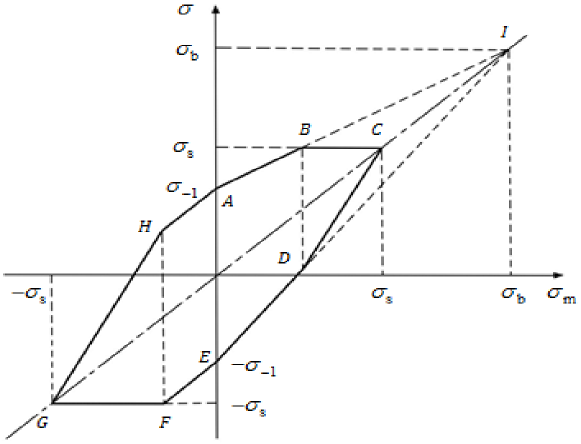

Fig.1 Goodman fatigue limit curve

Finite Element Analysis of Car Body Static Strength

Establishment of Car Body Finite Element Model

Aluminum alloy car body mainly uses large hollow extrusion profiles, which thickness dimension is much smaller than the size of the other two directions, so the stress changes in the thickness direction can be ignored. Due to the complexity of the forces, the car body need to withstand the longitudinal and transverse shear, vertical bending, longitudinal tensile and compression load, so the car body finite element model is established by using shell element. Selection of appropriate unit size, reference of the actual structure size and manual grid control to local position of car body make the whole model a better precision grid. The car body finite element model is shown in Fig.2 which contains 310,452 elements and 232,042 nodes.

The devices on car body are rigidly connected to the corresponding positions as lumped mass through the manner of MPC coupled nodes, including air conditioning, transformer and cooling device, auxiliary converter and equipment box(brake controlling unit and vehicle power supply). The specific coupling manner is shown in Fig.3. The mass of passengers and seats is applied on the floor through the way of uniform mass.

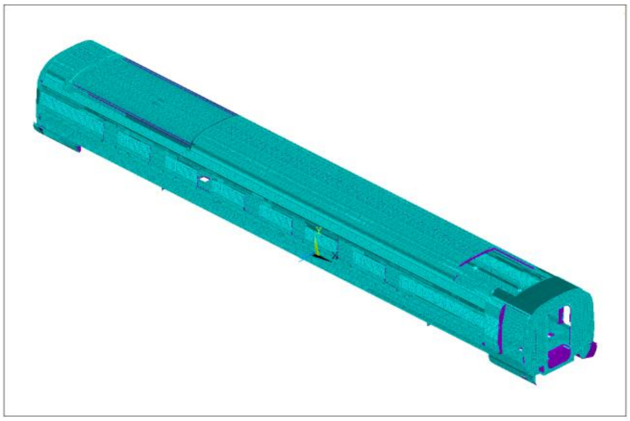

Fig.2 Car body finite element model

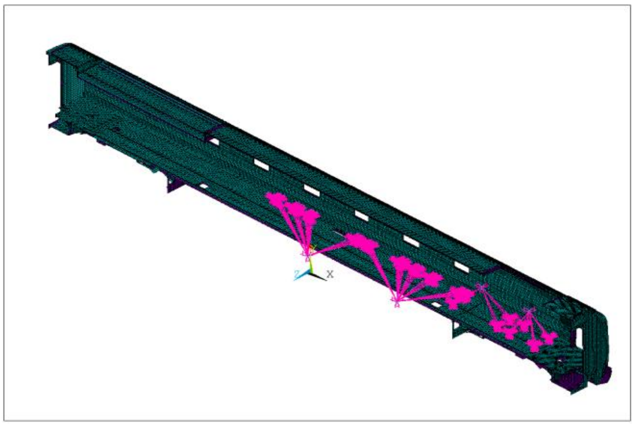

Fig.3 Devices connection diagram

Load Conditions for Evaluation Static Strength

The static strength loads of the aluminum alloy car body consists of the following components:

1) Vertical load, includes car body static load F_z and maximum working load $F_{z\max}$, which is shown in equation 1.

$$\begin{cases} F_z = m_1 g = (m_2 + p \bullet n + b \bullet s) g = 357.57kN \\ F_{z\max} = 1.3F_z = 464.84kN \end{cases} . \tag{1}$$

Among them, F_z is vertical load under operating state; m_1 is total mass under operating state; m_2 are weight of car body and mass of devices; p is mass of each passenger, taking 80kg per person, n is capacity number; b is baggage mass per unit area, taking 300kg/m^2, s is baggage counter area; g is acceleration of gravity, taking 9.81m/s^2.

2) Longitudinal load, includes longitudinal tensile load $F_{ls} = 1000kN$ and longitudinal compressive load $F_{ys} = 1500kN$.

Tab.2 Static strength calculation conditions

Condition	Load	Load manner and position	Constraints position
1	F_z	vertical acceleration on car body	Second air spring
2	$F_{z\max}$	vertical acceleration on car body	Second air spring
3	$F_z + F_{ls}$	vertical acceleration on car body and tension on first end coupler	Second air spring and second end coupler
4	$F_z + F_{ys}$	vertical acceleration on car body and compression on first end coupler	Second air spring and second end coupler
5	$F_z + p$	vertical acceleration on car body and Pressure difference inside and outside	Second air spring

3) Airtight load $p = 4000Pa$ is the pressure difference inside and outside the car body.

According to the standard *EN12663*, the intermediate car body static strength calculation conditions combined with the calculating characteristics of aluminum alloy car body strength are formulated[5,6,7].The specific load conditions and load manners are shown in Tab.2.

Strength and Stiffness Calculation Results

The car body stiffness is checked by equation 2 according to related design standards and data of car body[8,9]. Equation 2 is as follows:

$$EI_{eq} = \frac{W \bullet d_1^2}{384\delta}\left(5d_1^2 - 24d_2^2\right) \geq EI_{\min} \tag{2}$$

Among them EI_{eq} is equivalent bending resistance stiffness; W is vertical load of the vehicle longitudinal unit length; δ is center deflection of bottom chassis; d_1 is the distance between two bogies; d_2 is the distance from bogie center to car body ends. The specific content is shown in Fig.4.

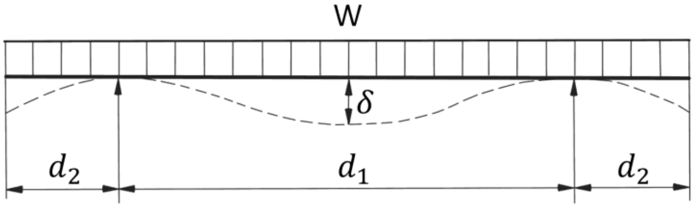

Fig.4 The schematic of stiffness checking parameters

The center deflection of bottom chassis is calculated by vertical load condition 1. The maximum deformation is 6.87mm,which located to the vehicle chassis longitudinal beam. The deformation is shown in Fig.5. The EI_{eq} is calculated by equation 2 as 1.43x10^9 $N \bullet m^2$,which large than the maximum design stiffness $EI_{\min}$=5.17x10^8 $N \bullet m^2$. It meets the stiffness requirement of car body.

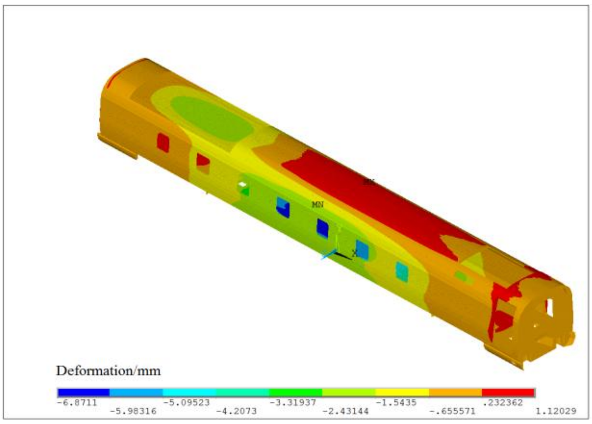

Fig.5 Deformation of car body

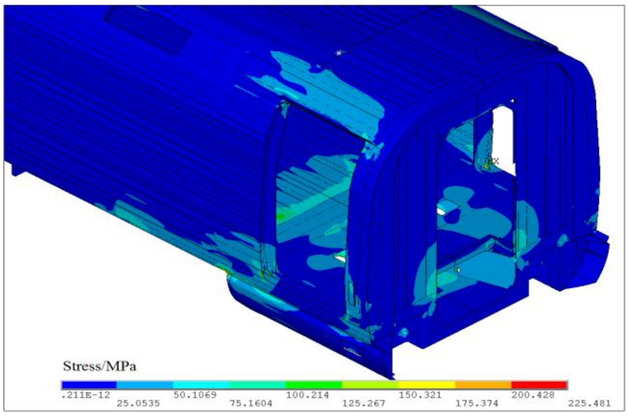

Fig.6 The Von Mises stress distribution

Tab.3 Calculation results of static strength

Condition	Maximum equivalent stress(MPa)	Position
1	127.913	device hanging place at bottom of car body
2	164.947	device hanging place at bottom of car body
3	126.756	device hanging place at bottom of car body
4	225.481	door corner
5	133.481	junction between chassis and sidewall

The maximum equivalent stress under all the load conditions is 225.481MPa,which appears in the corner of door of condition 4. The condition 4 is shown in Fig.6. The maximum equivalent stress of each conditions is shown in Tab.3. The larger equivalent stress positions are devices hanging place under car body, window corner, second end, first end coupler reinforcement board, junction between chassis and sidewall. While stress in the other parts of car body is small.

Condition 2 is operating condition among the above conditions. The material allowable stress is calculated as 197 MPa by taking safety factor S=1.5 which according to the *Interim Provisions*[10]. The material allowable stress beyond the maximum equivalent stress of condition 2. The other conditions are non-normal operating conditions and the material yield limit is 295 MPa which bigger than the maximum equivalent stress of condition 4. The results meet the requirement of static strength.

Fatigue Strength Evaluation for Car Body

Fatigue Strength Evaluation Method

Literatures of structure fatigue show that direction of fatigue cracks in the structure and the maximum principal stress directions perpendicular to each other[11]. According to the salient features of fatigue failure, the three-dimensional stress state is converted to the uniaxial stress state by the principle of maximum principal stress. The structure fatigue strength is evaluated based on Goodman correction curve after calculating mean stress and stress amplitude of stress cycles. The specific method is to determine the structure's principal stress and its direction of different load conditions, take the direction of structure's maximum principal stress $\sigma_{\max}$ under all load conditions as the basic stress direction, then project the principal stress of other load conditions onto the maximum principal stress direction. The minimum principal stress $\sigma_{\min}$ is the stress of which projection value is minimal. The projection process is shown in Fig.7. The transformation from multiaxial stress state to uniaxial stress state is completed by calculating mean stress σ_m, stress amplitude σ_a and stress ratio R through equation 3.

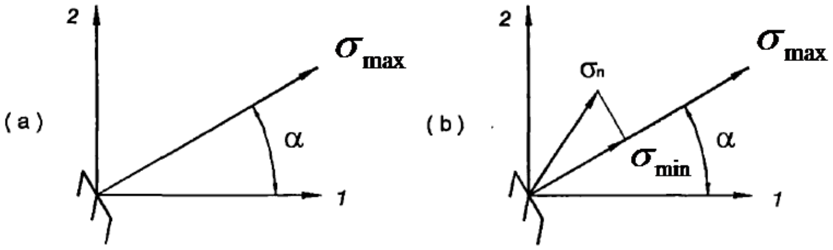

Fig.7 determination of maximum and minimum principal stress

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \quad \sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} \quad R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{3}$$

Evaluation of Car Body Fatigue Strength

Determination of Fatigue Strength Load Conditions. When the train is working, traction and braking of train lead to longitudinal dynamic load and vertical and lateral of track and irregular bending lead to vertical and transverse dynamic load. According to standard *EN12663*, longitudinal dynamic F_{xd}, transverse dynamic load F_{yd} and vertical dynamic load F_{zd} are expressed as equation 4:

$$F_{xd} = F_{yd} = F_{zd} = 0.15 m_1 g\ . \tag{4}$$

In order to simulate actual operating conditions, the F_{xd}, F_{yd} and F_{zd} should be considered together. The combination of fatigue load conditions are shown in table 4.Based on equation 3, the mean stress and stress amplitude of every nodes are calculated through programming in matlab, then the points are placed in the aluminum alloy Goodman fatigue limit diagram.

Tab.4 Load conditions for fatigue strength calculation

condition	load			condition	load		
	Longitudinal	Transverse	Vertical		Longitudinal	Transverse	Vertical
1	0	0	F_z	6	F_{xd}	F_{yd}	$F_z - F_{zd}$
2	F_{xd}	F_{yd}	$F_z + F_{zd}$	7	F_{xd}	$-F_{yd}$	$F_z - F_{zd}$
3	F_{xd}	$-F_{yd}$	$F_z + F_{zd}$	8	$-F_{xd}$	F_{yd}	$F_z - F_{zd}$
4	$-F_{xd}$	F_{yd}	$F_z + F_{zd}$	9	$-F_{xd}$	$-F_{yd}$	$F_z - F_{zd}$
5	$-F_{xd}$	$-F_{yd}$	$F_z + F_{zd}$	10	p		F_z

Fatigue Strength Evaluation Results. The points placement of whole car body in Goodman fatigue limit diagram are shown in Fig.8. The solid line is the weld zone area while dashed area is the base metal zone. All points are in the closed area of Goodman curve. The safety factor of all nodes are calculated lager than 1, it means the car body achieves the infinite life design criteria and meets the requirement of fatigue strength. The fatigue strength calculation results of 10 nodes are shown in Tab.5. The minimum safety factor of all nodes is node 77061 as 2.41 and it has a large margin of safety.

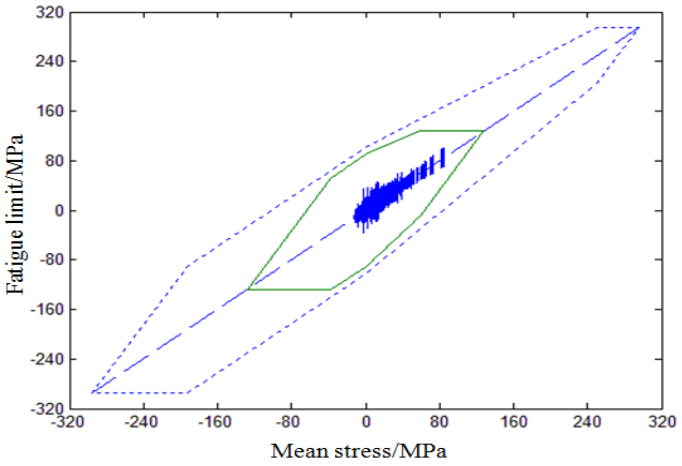

Fig.8 The whole car body fatigue strength evaluation

Tab.5 Fatigue strength evaluation results

Nodes number	principal stress (MPa)		Mean stress (MPa)	Stress amplitude (MPa)	Load condition of maximum principal stress	Load condition of minimum principal stress	Safety factor		Node position in model		
	max	min					Non-weld zone	Weld zone	x (mm)	y (mm)	z (mm)
77061	35.4	-39.2	-1.92	37.3	10	5	2.73	2.41	11941	1266	-555
67394	45	-20	12.5	32.5	10	4	3.05	2.63	-4810	3550	-897
3974	35.9	-24.1	5.93	30	10	5	3.35	2.93	5740	1180	-1400
86470	34.4	-16.7	8.86	25.5	10	6	3.92	3.4	10600	3510	-1310
67279	19.9	-21.4	-0.72	20.7	4	10	4.93	4.35	-4810	3500	-1120
45712	101	68.5	84.6	16.1	5	6	5.13	2.7	-3150	1020	-1440
6432	24.2	-15.3	4.46	19.7	4	7	5.13	4.49	815	1100	-1400
37764	10.8	-28.2	-8.7	19.5	8	10	5.23	4.62	9810	1180	-422
6887	18.6	-16.9	0.84	17.7	4	2	5.75	5.07	5670	1100	-1400
45713	87	59.1	73	14	5	6	6.09	3.93	-3090	1020	-1440

Conclusion

Through finite element analysis to the aluminum alloy car body , this paper obtains following conclusions:
(1) Combined with mechanical characteristics of aluminum, the aluminum alloy Goodman fatigue limit diagrams are drawn and are taken it as the main basis for the fatigue strength evaluation.
(2)According to the standard *EN12663*, the static and fatigue strength load conditions are determined. Through finite element calculation, the maximum equivalent stress of car body is less than material allowable stress, which meet the requirement of strength.
(3) Using the principle of maximum principal stress, the multi-axial stress is converted to uni-axial stress. The car body fatigue strength is evaluated combined with aluminum alloy Goodman curve. The whole structure of car body meets the requirement of fatigue strength and it provides reference to car body lighweight design.

Acknowledgement

This research was supported by the National Natural Science Foundation of China (Grant No. 51275428), Also this research was supported by the Fundamental Research Funds for the Central Universities (SWJTU12CX035) and the Open Foundation of Traction Power State Key Laboratory (TPL1213).

References

[1]Liu Jingan,Wang Yuanliang,Qu Jinshan. Welding characteristics of aluminum alloys for railway vehicles[J], Transactions of Nonferrous Metals Society of China,1996, 6(6):87-92.

[2]Yao Shuguang,Xu Ping. Chinese domestic components of high-speed maglev train body[J]. Journal of traffic and transportation engineering, 2004, 4(2):40-44.

[3]Lu Yaohui,Feng Zhen,Chen Tianli,et al.Evaluation method of fatigue strength for car body of high-speed train under influence of aerodynamic loads[J]. Journal of traffic and transportation engineering,2014,14(6):44-50.

[4]Seo Sung II, Park Choon-Soo, Kim Ki Hwan. Fatigue Strength Evaluation of Aluminum Alloy.

Car body of Vehicles by Large Scale Dynamic Load Test[J].Foreign Rolling Stock, 2009,46(2):27-32.

[5]Guo Xiangtao. The Structure Analysis of High — speed EMU Body and the Optimization Base on Sensitivity Analysis [D].Beijing:Beijing Jiaotong University, 2011.

[6]Qu Sheng. Study on fatigue strength of car body of high-speed train[D].Chengdu:Southwest Jiaotong University, 2013.

[7]Beuth Verlag Gmb H.EN12663-1/2010.Structural Requirements of Railway Vehicle bodies[S].Berlin:CNE, 2010.

[8]Wu Rrenen. The Researeh on FEA of Aluminum-alloy car body Structure Based on ANSYS [D].Beijing:Beijing Jiaotong University, 2008.

[9]Japanese Industrial Standards Committee.JIS E7106:2006. Rolling Stock. General Requirements of Car body Structures for Passenger Car[S]. Tokyo, Jpn.Ind.Stand.2006.

[10]Bai Yanchao,Zhang Shuoshao,Hu Zhen,et al. Research on Design Technology for Aluminum-alloy Car body Strength of CRH_3 EMU[J].Railway Locomotive&Car, 2013, 33(2):16-20.

[11]LuYaohui. Study on fatigue reliability of welded bogie frame for railway vehicle[D]. Chengdu: Southwest Jiaotong University, 2011.