Research on Fatigue Test Method of Car Body for High-speed trains

Chao Wang¹*, Chengqiang Wang¹, Chaotao Liu², Yongzhi Jiang²

¹ CRRC Changchun Railway Co. Ltd., Changchun, Jilin, 130062, China
² State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu, Sichuan, 610031, China

*Corresponding author’s e-mail: wangchao.a@cccar.com.cn

Abstract. The car body of high-speed train bears all the static and dynamic loads. An accurate strength analysis of critical point is crucial for its fatigue design. Since a fatigue analysis is dependent on the load amplitude and its application point on car body, the loads applied in the fatigue test is studied by using the strength test bench. A comparative study was performed among the relevant standards concerns the car body fatigue. In addition, a specific test scheme is promoted, and the applied loads on vertical, lateral, longitudinal and torsional directions on car body under various spectrums are thoroughly determined. This study provides a basic fatigue test bench of car body for high-speed trains with the specific loads application and test schemes. This allows the body to be subjected to random loads and provides a basis for the specifications of follow-up fatigue tests on the car body and its components.

1. Introduction
With the increase of commercial speeds of high-speed trains on conventional tracks in China, the car body structures of these vehicles are subject to serious fatigue problems. A general strength evaluation method of car body is to perform a static load test and finite element analysis (FEA). However, the evaluation of fatigue strength of railway vehicle components could not be performed well due to the fact that the structural failure is mainly caused by the dynamic random loads. It is particularly important to find out the weak parts of car body. However, the research on the car body fatigue test is very limited.

The FEA and tests on rig are two essential techniques used during the car body strength design. The simulation has the advantages of high efficiency and low cost, whereas the test can verify the accuracy of simulation, but also consider others factors. Since the fatigue analysis of car body is dependent on the load and its application position, a comparative study was performed among the relevant standards in the loads definition. In addition, a specific fatigue test scheme for the car body of high-speed trains is promoted and verified on a newly designed test rig.

A quasi-static stress analysis method is a commonly used time domain approaches to analyze the dynamic stress for fatigue assessment [1]. A linear elastic analysis is that the external load history acting on the structure can be replaced by a static unit load acting on the same location in the same direction as the load history. The quasi-static stress analysis is then performed for each individual unit loads. A multi-disciplinary analysis method is proposed for evaluating the fatigue life and durability of car body under random dynamic loads [2]. The necessity of evaluating aluminum alloy car body fatigue strength with a large dynamic load test method in introduced in reference [3]. The car body
material's Goodman curve according to the mechanical properties of aluminum alloy and specification was declared in EN 12663 as well as the related car body fatigue assessment [4]. In the fatigue analysis of the aluminum alloy car body, the influence of aerodynamic loads was also considered [5]. Lab tests for the fatigue strength testing of the underframe of car body are proposed for railway vehicles [6], in which the basic process of reproducing the load spectrum is analyzed. The vibrational state of the car body is accurately simulated on the test rig, which allows the body to be subjected to random loads. This investigation provides a basis for the specifications of follow-up fatigue tests on the car body and its components.

2. Background
At present, there are not detailed rules for the specific implementation of the fatigue test of car body. Use fatigue tests on car body, fruitful studies can be achieved. Figure 1 depicts the test rig in Korea, and the Association of American Railway (AAR) has established a car body fatigue test rig, which has carried out a large number of fatigue tests for freight wagons, as shown in Fig.2. The rig uses an inertia loading method to carry out the fatigue life test. The acceleration signal on car body and the nodal stress or force on coupler are used to accelerate the test, and the accelerated load spectrum is reproduced.

Qiqihar Rolling Stock Co., Ltd. (QRS) in China built a car body fatigue test rig and a vibration test rig for relevant experiments for freight wagons. The input signal is used from actuators for loading is adjusted in real time according to the back feed of target signal. The time history of strain and acceleration of car body was measured and processed. The fatigue test rig in Southwest Jiaotong University (SWJTU) in China is a multi-channel, multi loading mode and multi-function test rig. The vibration load can be provided by two six degree-of-freedoms (DOFs) excitation platforms, then loads can be applied in three directions simultaneously. The rig also has the ability for the airtight loading, and the air tightness of the car body can be detected with the car body sealed and air filled. Using those car body fatigue test rigs, the fatigue life for freight wagons and high-speed trains can be verified.
3. Car Body Loads Study on the Fatigue Test Rig

3.1 Regulation of fatigue load of car body from standards
TB/T3541 ‘Strength design and test of the body structure of EMU body’ declares that the car body should be able to bear loads more than 10 million times in three directions which are applied separately. It is \( \pm 0.15g \times (m_1 + m_3) \) in \( x \) and \( y \) directions and \( 1 \pm 0.15g \times (m_1 + m_3) \) along \( z \) direction in which \( m_1 \) is for the mass of the car body under and \( m_3 \) denotes for the actual load.

EN 12663-1:2010+A1:2014 ‘Railway application - railway vehicle body structure requirements’ defines the same loads in TB/T3541, but their combinations are not specified. In addition, the load conditions in the interface between the car body and bogie are required to be examined as specified in EN12663. The loads consider the starting, braking, torsion and shock absorber loads.

EN13749-2011 ‘Railway application-the prescribed method of wheelset and bogie, bogie structure’ provides more specifications for the interface load between the car body and bogie, such as the operating conditions, the load caused by braking is 1.1 times the rated braking load, and the load of shock absorber is the unloading of the damper.

The fatigue load of subway and low-floor car body is divided into three types according to VDV152-2016 ‘Recommendation on the Design for Strength of Urban Rail Rolling Stock according to BOStrab’, as listed in Tab.1. For tangent and curved tracks and acceleration/deceleration cases, it works for 6 million times. The load is same as defined in the EN12663. Although the VDV152 aims at the subway car, the load condition can be used in the fatigue analysis for high-speed vehicles.

JIS E 7106:2006 ‘General requirements for the design of railway locomotives’ specifies the lateral and vertical loads as that in EN12663, and provides a torsional load of 40 kN.m. While this standard does not specify the longitudinal load.

Table 1. Loads in VDV152-2016 for subway and low-floor car body

| Load condition                  | x-direction | y-direction | z-direction | Cycles  |
|--------------------------------|-------------|-------------|-------------|---------|
| Tangent tracks                 | /           | ±0.12 g     | -1 ± 0.19 g | 6 million |
| Curved tracks                  | /           | ±0.16 g     | -1 ± 0.1 g  | 6 million |
| Acceleration and deceleration  | ±0.15 g     | ±0.06 g     | -1 ± 0.1 g  | 6 million |

3.2 Determination of test loads

3.2.1 Vertical load. Vertical load consists of two parts, the static load and dynamic load. Considering the operating conditions of high-speed train, the static load is set as \( (m_1 + m_3)g \) in TB/T3541. It is 0.15 \( g \) plus the gravity of car body as defined in the European standard and the Japanese standard.

3.2.2 Lateral load. The lateral load includes the lateral loads of air spring and the central pin. Because the load of air spring is much smaller than that of central pin, only the lateral load of central pin is considered in the test. So it is 0.15 \( g \) plus the mass moment of inertia.

3.2.3 Longitudinal load. The longitudinal load is 0.15 \( g \) defined in TB/T3541 and EN12663. If the inertia load is adopted, the same displacement excitation should be applied on two couplers and two center-pins to make the body vibrate meet the target level. While this loading mode will not benefit for the force distribution on components, and the phase relation of the load may also be contrary to the phase relationship during start or brake. It is suggested to adjust the load when evaluating the sleeper beam. However, for the fatigue test of the whole structure, a lot of suspended equipment on car body and the connecting point needs to be considered as well. Only using the force loading mode will make the stress on the hanging point deviate from the real value. Therefore, after the fatigue test, it is recommended that the inertia loading is used to supplement the longitudinal load for the suspended equipment.

The EN13749 specifies the load for starting and braking conditions, which can be converted into
the acting force of each bogie to the car body by the following equation.

\[ F_x = 1.1a \frac{m_v + 1.2P_s - n_bm^+}{n_b} \]  

(1)

Here, \( m_v \) is the vehicle mass, \( a \) the starting or braking acceleration, \( P_s \) the load, \( n_b \) the number of bogies, \( m^+ \) the bogie mass. In case of an inertia loading test, 0.15 g is used in EN12663.

### 3.2.4 Distortion load

The JIS E 7106 specifies the distortion load is 40 kN.m, but the other standards do not mention it. This is mainly due to the large longitudinal load required in the European standard, which generally meets the strength requirements and can also meet the stiffness requirements of car body. It is necessary to limit the body stiffness because of the smaller longitudinal load and the lightweight structure of the car body in Japan.

### 3.2.5 Load spectrum compilation for fatigue test

Cyclic load is the external cause of fatigue failure, so the compilation of test load spectrum is particularly important. Except for VDV152, other standards do not define stipulates on the compilation of load spectrum, and VDV152 is only suitable for subway and low-floor vehicles. The fatigue life requirement of car body for high-speed trains is 15 million km, which is much higher than that in Europe and Japan. UIC515-4:1993 ‘Structural strength test of passenger vehicle-Trailor bogies-walking device-bogie frame’ mentions that the cycles of fatigue test can fully simulate the conditions of running condition for 200 thousand km and 30 years. Therefore, in the absence of the measured load spectrum, the method of the load spectrum compilation of this test is carried out according to the UIC standard.

The load spectrum of this test is divided into main test sand supplementary test. The times of load cycles for the main body and the supplementary parts are 10 million which is additionally divided into three phases. The first 6 million times names the first phase, and 6-8 million times is the second phase, and 8-10 million times means third phase, as shown in Tab.2. In the second and third phases, the dynamic load is 1.2 times and 1.4 times that of the first phase, respectively.

| Loads         | Main test |  |  |  | Supplementary test |
|---------------|-----------|---|---|---|-------------------|
|               | First     | Second | Third | First | Second | Third |
| Longitudinal  | \( F_x \) | 1.2\( F_x \) | 1.4\( F_x \) | \( \pm0.15 \) g | \( \pm0.18 \) g | \( \pm0.21 \) g |
| Lateral       | \( \pm0.15 \) g | \( \pm0.18 \) g | \( \pm0.21 \) g | 0 | 0 | 0 |
| Vertical      | 1\( \pm0.15 \) g | 1\( \pm0.18 \) g | 1\( \pm0.21 \) g | 0 | 0 | 0 |

### 4. Test Scheme for the Car Body Fatigue Test

According to the load spectrum proposed in Section 3, the car body fatigue test of high-speed trains was carried out by using the test rig in SWJTU shown in Fig.5. The body was supported on two six DOFs platforms in Fig.6. Each platform can realize the translational and rotational movements. Connections between the car body and the platform are set according to the actual loads on car body. The air-spring seat only bears the vertical load, and the center-pin bears both the lateral and longitudinal loads.

Figure 5. Loading scheme for the fatigue test of car body

For the vertical loads of the secondary suspension, tools are installed on each six DOFs platform.
The lateral and longitudinal freedoms are released through linear bearings. A load sensor is arranged between the tools and loading points on car body. Moreover, rubber pads are arranged at connecting points to avoid rigid impacts in the test, see Fig.7. The center-pin loading tool is installed on the platform as shown in Fig.8. The tool connects the false center-pin and the test platform through a spherical joint. Two longitudinal actuators are arranged in the position of two couplers to simulate the coupler force, as shown at the car body end in Fig.5. The six DOFs platform is equipped with 2 longitudinal actuators at the vertical and horizontal positions to balance the unbalanced longitudinal from couplers.

5. Summary and Conclusions
In this investigation, the load of the car body fatigue test of the high-speed train is determined by comparing various standards, and then the test loading scheme is promoted for the fatigue test rig built in Southwest Jiaotong University in China. A comparative study was performed among the relevant standards from various authorities used for evaluating the car body strength and fatigue. In addition, the specific fatigue test scheme is promoted, then a thorough fatigue test for a high-speed train body was conducted. The applied loads on vertical, lateral, longitudinal and torsional directions on car body under various spectrums are thoroughly determined according to related criterion. The investigation of this study provides a basic fatigue test bench of car body for high-speed trains with the specific loads application and test schemes introduced. This allows the body to be subjected to random loads and provides a basis for the specifications of follow-up fatigue tests on the car body and its components.

Acknowledgements
This research was supported by the project of National Key R&D Program of China under Grant No. 2016YFB1200506-001.
References

[1] Haiba, M., Barton, D.C. and Brooks, P.C. (2002) Review of life assessment techniques applied to dynamically loaded automotive components. Computers & Structures, 80:481-494.

[2] Miao, B., Zhang, W., Zhang, J., et al. (2009) Evaluation of railway vehicle car body fatigue life and durability using multi-disciplinary analysis method. International Journal of Vehicle Structures & Systems, 1:85-92.

[3] Sung, S., Choon-Soo, P. and Hwan, K.K. (2009) Fatigue strength evaluation of aluminum alloy car body of vehicles by large scale dynamic load test. Foreign Rolling Stock, 46:27-32.

[4] Xie, N., Lu, Y. and Feng Z., et al. (2015) Fatigue strength research on aluminum alloy car body for railway vehicle based on finite element analysis method. International Conference on Material Science and Application, ICMSA 2015, 885-891.

[5] Lu, Y., Feng, Z., Chen, T., et al. (2014) Evaluation method of fatigue strength for car body of high-speed train under influence of aerodynamic loads. Journal of traffic and transportation engineering, 14:44-50.

[6] Song, Y., Wu, P. and Jia, L. (2015) Study of the fatigue testing of a car body underframe for a high-speed train. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 230: 1614-1625.