Simulation and Optimization Design of CRH380A EMU Bogie Frame

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Abstract. Taking SKMB-200 power bogie frame applied to CRH380A EMU as the research object, based on UIC615-4 standard, four kinds of simulated operating conditions load and one kind of supernormal load are calculated, and then constraints and loads required for ABAQUS simulation analysis are determined. The results of static strength simulation show that the maximum stress of the frame under simulated operation conditions, and under abnormal load conditions are lower than the allowable stress of the main material SMA490BW weathering steel. The static strength of the frame meets the standard. Then, through setting design variables, selecting constraints and determining the objective function, the structural optimization analysis of the selected abnormal load cases is carried out. The optimization results show that the total mass is reduced by 109 kg, which is 6.8% lower than that before optimization, and the maximum equivalent stress value of the frame is 329.98 MPa, which still meets the strength requirements. By optimizing the structural parameters of the frame, the under-spring mass of SKMB-200 bogie can be effectively reduced, and its dynamic performance can be improved, which can provide reference for the optimum design of the bogie structure of EMU.

Keywords: Bogie frame; EMU; Finite element simulation; CRH380A.

1. Introduction

The bogie, as the running part of the high-speed EMU, carries the car body, contacts the track, and traction and guides the vehicle to drive along the track, which has an important impact on the stability, smoothness and safety of the EMU operation. And the frame is its main bearing part, each part on the bogie must be installed in the frame and form a whole. Therefore, the bogie frame of EMU must be strong enough to ensure the safety of train operation[1].

At present, Chinese scientists and technicians have made some research in the field of frame strength and fatigue checking. For example, Liang et al.[2] took the CRH2 EMU bogie frame as the research object, and carried out the prediction of fatigue life and reliability evaluation of the larger stress parts in combination with the S-N fatigue curve; Jin et al.[3] checked the strength of the frame of the CRH5 EMU according to UIC615-4; Feng et al.[4] explored the static strength of the bogie frame under supernormal conditions and simulated operating conditions, and added the static load and dynamic load of the frame under different conditions to check the rationality of the frame design again.

However, most of the researches on the structure still focus on strength checking and fatigue analysis at present, while few on its optimal design[5]. Therefore, this paper intends to use ABAQUS and Hyperworks to study the SKMB-200 power bogie frame applied to the type of CRH380A EMU, and carry out simulation analysis and propose optimization scheme, and provide reference to the design and optimization of the power bogie frame of the EMU.
2. Basic Processing of 3d Model

2.1. Mesh generation
SKMB-200 bogie frame is mainly welded by left and right side beams, two beams and longitudinal connecting beams. The main bearing members of the frame are made of SMA490BW type weather resistant steel conforming to JISG3114 standard, and other parts are made of alloy structural steel. Limited to space, this paper lists the elastic modulus, density, Poisson's ratio and other parameters of SMA490BW steel, as shown in Table 1.

| Model       | Strength of extension | Yield strength | Modulus of elasticity | Poisson's ratio | Density          |
|-------------|-----------------------|----------------|-----------------------|-----------------|------------------|
| SMA490BW    | 490MPa                | 355MPa         | 2.0×10^5MPa          | 0.29            | 7800kg/m^3       |

In this paper, referring to the geometric parameters of SKMB-200 bogie frame, the 3D solid model is established in Solidworks, as shown in Figure 1. Then the model is saved as IGES format and imported into ABAQUS for grid division.

![Figure 1. 3D model of SKMB-200 bogie frame.](image)

Due to the complexity of the frame shape, this paper adopts the combination of automatic mesh generation and manual generation, and selects C3D10 type and tetrahedron shape to divide the model into 43013 units and 72071 nodes[6]. The meshed model is shown in Figure 2.

![Figure 2. Grid division.](image)

2.2. Setting constraints
The actual working condition of SKMB-200 bogie in service must be fully considered when setting the constraints. The constraints added in this paper include displacement constraints and elastic constraints. Adding the spring restraint at the axle box spring seat and the positioning pin seat of the swivel arm. The vertical rigidity, the transverse rigidity and the longitudinal rigidity of the axle box spring seat are 1.244kN/mm, 0.98kN/mm, and the transverse rigidity of the positioning pin seat of the swivel arm is 5.49kN/mm. Adding the longitudinal elastic restraint at the traction rod of the crossbeam. The displacement constraint is set as the displacement constraint of four primary springs relative to the ground.
3. Static Strength Load Calculation

3.1. Load calculation method

In the UIC615-4 standard, the static strength load test of the bogie frame includes abnormal load test and simulated operation load test. The schematic diagram of the frame load is shown in Figure 3. Vertical load, transverse load and oblique symmetrical load are included in the supernormal load and simulated operation load[7].

![Figure 3. Diagram of bogie frame loading.](image)

1) Load calculation under simulated operating conditions

a) Vertical load

The vertical load acts on the left and right air spring support beams of the frame, and the calculation formula is as follows:

\[ F_z = \frac{g \cdot (m_v + 1.2C_1 - 2m^+)}{4} \]  
\[ (1) \]

In formula:

- \( F_z \)—— Vertical load of each side under simulated operation condition, N;
- \( g \)—— Acceleration of gravity, 9.8 m/s²;
- \( m_v \)—— Empty vehicle mass in operation stage, 35880kg;
- \( C_1 \)—— Passenger mass during simulated operation, 19200kg;
- \( m^+ \)—— Bogie mass, 7300kg.

b) Lateral load

\[ F_y = 0.5 \times (F_z + 0.5m^+ g) \]  
\[ (2) \]

In formula:

- \( F_y \)—— Lateral load under simulated operating conditions, N;
- \( F_z \)—— Vertical load under simulated operating conditions, N;
- \( m^+ \)—— Bogie mass, 7300kg;
- \( g \)—— Acceleration of gravity, 9.8 m/s².

c) Oblique symmetrical load

It is necessary to consider the load caused by the track's five-thousandths of a twist under simulated operating conditions.

2) Load calculation under abnormal working condition

a) Vertical load

\[ F_{z1\text{max}} = F_{z2\text{max}} = \frac{1.4 \times g \cdot (m_v + C_2 - nm^+)}{2nb} \]  
\[ (3) \]

In formula:

- \( F_{z1\text{max}} \)—— Vertical load on the left side under abnormal conditions, N;
- \( F_{z2\text{max}} \)—— Vertical load on the right side under abnormal conditions, N;
- \( g \)—— Acceleration of gravity, 9.8 m/s²;
- \( m_v \)—— Empty vehicle mass in operation stage, 35880kg;
- \( C_2 \)—— Passenger mass under overloaded operation, 27800kg;
- \( m^+ \)—— Bogie mass, 7300kg;
- \( nb \)—— Number of bogies under a single carriage, 2.

b) Lateral load
\[ F_{\text{ymax}} = 2 \times \left[ 10^4 + ((m_v + C_2)g)/(3n_en_b) \right] \]

In formula:
- \( F_{\text{ymax}} \) — Lateral load under abnormal conditions, N;
- \( m_v \) — Empty vehicle mass in operation stage, 35880 kg;
- \( n_e \) — Number of axles per bogie, 2;
- \( n_b \) — Number of bogies under a single carriage, 2;
- \( C_2 \) — Passenger mass under overloaded operation, 27800 kg;
- \( g \) — Acceleration of gravity, 9.8 m/s².

c) Oblique symmetrical load
It is necessary to consider the load caused by the track's five-thousandths of a twist under simulated operating conditions.

3.2. Load calculation under different operating conditions
According to UIC615-4 standard, we can get 15 different working conditions, including 2 kinds of abnormal load conditions and 13 kinds of simulated operating load conditions[8]. Due to space limitations, this article chooses five different operating conditions for analysis, among which operating conditions 1 to 4 are simulated operating conditions, and operating condition 5 is an abnormal load condition.

In the calculation of the load, the influence of the curve factors on the bogie must also be taken into account[9]. In order to simulate the change of vertical load caused by rolling and vertical movement of the vehicle body, the roll coefficient \( \alpha = 0.1 \) and the rising and settling coefficient \( \beta = 0.2 \) are taken.

According to UIC615-4 standard, the load calculation table of each working condition can be obtained, as shown in Table 2. Combined with the above formula and relevant data, the load of case 1 to case 5 can be calculated in turn, and the load value required for ABAQUS simulation can be determined.

**Table 2.** Load calculation table for each working condition.

| Number | Vertical right and left loads | Lateral load | Oblique symmetrical load |
|--------|-------------------------------|--------------|-------------------------|
| Case 1 | \( F_z \)                     | 0            | Force due to 25 mm displacement |
| Case 2 | \((1+\alpha-\beta)F_z\)       | \((1-\alpha-\beta)F_z\) | Force due to 25 mm displacement |
| Case 3 | \((1+\alpha-\beta)F_z\)       | \((1-\alpha-\beta)F_z\) | Force due to 25 mm displacement |
| Case 4 | \((1-\alpha-\beta)F_z\)       | \((1+\alpha-\beta)F_z\) | Force due to 25 mm displacement |
| Case 5 | \( F_{z1\text{max}} \)       | \( F_{z2\text{max}} \) | Force due to 25 mm displacement |

Load calculation in case 1:
\[ F_z = 9.8 \times (35880 + 1.2 \times 19200 - 2 \times 7300) / 4 = 108584 \text{N} \]

Load calculation in case 2:
\[ F_z1 = (1+0.1-0.2) \times 108584 = 97725.6 \text{N} \]
\[ F_z2 = (1-0.1-0.2) \times 108584 = 76008.8 \text{N} \]

Load calculation in case 3:
\[ F_z1 = (1+0.1-0.2) \times 108584 = 97725.6 \text{N} \]
\[ F_z2 = (1-0.1-0.2) \times 108584 = 76008.8 \text{N} \]
\[ F_y = 0.5 \times (0.5 \times 7300 \times 9.8 + 108584) = 72177 \text{N} \]

Load calculation in case 4:
\[ F_z1 = (1-0.1-0.2) \times 108584 = 76008.8 \text{N} \]
\[ F_z2 = (1+0.1-0.2) \times 108584 = 97725.6 \text{N} \]
\[ F_y = 0.5 \times (0.5 \times 7300 \times 9.8 + 108584) = 72177 \text{N} \]

Load calculation in case 5:
\[ F_{z1\text{max}} = F_{z2\text{max}} = 1.4 \times 9.8 \times (35880 + 27800 - 2 \times 7300) / 4 = 168344.4 \text{N} \]
Fymax = 2 × [10000 + 9.8 × (35880 + 27800)/12] = 124010.7N

4. Simulation Results and Analysis

The cloud chart of equivalent stress distribution of SKMB-200 bogie frame under different load conditions is shown in Figure 4. The location and magnitude of the maximum equivalent stress are shown in Table 3.

Table 3. Table of maximum stress position and its magnitude under various working conditions.

| Load conditions | Position of the maximum stress                           | Stress   |
|-----------------|---------------------------------------------------------|----------|
| Case 1          | Position of circular hole of side member lower cover plate | 225.7MPa |
| Case 2          | Position of circular hole of side member lower cover plate | 209.0MPa |
| Case 3          | Attachment of transverse stop and beam                  | 250.3MPa |
| Case 4          | Position of circular hole of side member lower cover plate | 196.2MPa |
| Case 5          | Attachment of transverse stop and beam                  | 307.6MPa |

It is known that the yield limit of SMA490BW is 355MPa. It can be seen from Table 3 that the maximum stress that can be achieved under simulated operation condition load is 250.3MPa, and the maximum stress that can be achieved under abnormal condition load is 307.6MPa.

![Figure 4. Cloud chart of equivalent stress distribution of frame.](image)

5. Optimal Design

As mentioned above, the bogie frame is made of SMA490BW type weather resistant steel, its allowable stress is 355MPa, and the maximum equivalent stress value obtained in the static strength simulation analysis is 307.6MPa, so there is still a certain structural safety margin for the frame, and the frame can be optimized to a certain extent[10]. In this paper, the structural optimization analysis is carried out with the load with the maximum stress value of the previous analysis.

5.1. Optimize pre-treatment
5.1.1. Design variable
The frame consists of plate and solid, and its side beam consists of upper and lower cover plates and inner and outer side plates. In this paper, four plate thicknesses are selected as design variables, which are the upper and lower cover plates and inner and outer side plates of the side beam.

5.1.2. Objective function
The optimization analysis of the framework is to ensure that when the strength of the framework meets the requirements, the quality decreases with the change of variables, so the minimum quality of the framework is the objective function of this paper[11].

5.1.3. Constraint condition
This paper selects the strength standard of the framework of UIC. The maximum stress of the framework is required to be less than the allowable stress of the material, which is 355MPa. Considering the safety margin, this paper determines that the maximum equivalent stress is less than 330MPa.

5.2. Process of optimization analysis
The model is preprocessed again by Hyperworks, including defining material attributes, meshing, adding loads and constraints, and so on; and the model is divided into three parts: optimization design area, non optimization area and unit connection; shell element is used to mesh the optimized area, solid element is used to mesh the non optimized area, and the connection between the two areas is simulated by solder joint; then add the design variables, set the initial value of the upper and lower cover plates as 27mm, the initial value of the inner and outer side plates as 20mm; after the design variables are defined, the objective functions and constraints defined above are defined by volume response and stress response. The results of optimization are shown in Figure 5 and Figure 6.

![Figure 5. Cloud thickness map after optimization.](image1)

![Figure 6. Equivalent stress cloud diagram optimization.](image2)

It can be seen from the simulation results that the thickness of the upper and lower cover plates of the optimized rear side beam is 18mm, the thickness of the inner and outer side plates is 20.5mm, the total weight of the frame is reduced by 109kg, and the lightweight is 6.8%. The maximum equivalent stress after optimization is 329.98MPa, which still meets the strength requirements.

6. Conclusion
During the service process of the EMU bogie, its frame must have sufficient strength to ensure the safe driving of the train. In this paper, the SKMB-200 power bogie frame applied to CRH380A EMU is
taken as the research object, and its structural strength is simulated and analyzed by ABAQUS and Hyperworks. Conclusion as follows:

(1) According to UIC615-4 standard, five load cases were selected for static strength simulation analysis in ABAQUS software. According to UIC 615-4 standard, five load cases were selected for static strength simulation analysis in ABAQUS and the results shows that under simulated operating conditions, the maximum stress values of the frame are 225.7MPa, 209.0MPa, 250.3MPa, and 196.2MPa, and under normal load conditions, the maximum stress value of the frame is 307.6MPa. Because the allowable stress of the main frame material SMA490BW weathering steel is 355MPa, the static strength of the frame in the above working conditions meets the standard, there is no strength yield phenomenon, and there is a certain structural safety margin.

(2) In the Hyperworks, the structure optimization analysis of the frame is carried out under the abnormal load condition. The thickness of the upper and lower cover plates of the side beam and the inner and outer side plates are set as the design variables, the maximum equivalent stress value as the constraint conditions, and the minimum mass of the frame as the objective function. The results showed that the thickness of the upper and lower cover plate of the side beam after optimization was changed to 18mm, and the thickness of the inner and outer cover plate was changed to 20.5mm, and the total mass was reduced by 109kg, 6.8% lower than that before optimization. The maximum equivalent stress value of the frame is 329.98MPa, which still meets its strength requirement. The unsprung mass of the SKMB-200 bogie can be effectively reduced by optimizing the structural parameters of the frame, thereby improving its dynamic performance, which can provide a reference for the design and structural optimization of the EMU bogie.

References
[1] Zheng W. “Structure strength and reliability analysis of CRH380B bogie frame,” Master's Thesis, Lanzhou Jiaotong University, China, 2017.
[2] Liang H Q, Cai H, Zhao Y X, and Liu S Y, “Fatigue reliability analysis of welded joints for bogie frame of high-speed passenger car,” Mechanical Science and Technology for Aerospace Engineering, vol. 34, pp. 925-929, 2015.
[3] Jing Z Y, and Ma S Q, “Optimized design of welded frame of CRH5 EMU bogies,” Rail Transportation Equipment and Technology, pp. 25-28, 2009.
[4] Feng Z W, Tang Y M, and Sun H D, “The static strength and fatigue strength test for welding bogie frames for multiple units,” Foreign Rolling Stock, vol. 46, pp. 19-21, 2009.
[5] Zhi P P, Li Y H, and Chen B Z, “Structural strength analysis of bogie frames considering parameter uncertainty,” China Mechanical Engineering, vol. 30, pp. 22-29, 2019.
[6] Jiang Q H, “Research on strength and modal of welded frame for 160km/h rapid wagon bogie,” Southwest Jiaotong University, China, 2011.
[7] Wang B J, Sun S G, Wang X, Zhang L, and Dong L, “Research on characteristics of operation loads and fatigue damage of metro train bogie frame,” Journal of the China Railway Society, vol. 41, pp. 53-60, 2019.
[8] Dong B, and Wang M, “Evaluation Method for Influence Degree of External Load on Static Strength of Railway Vehicle Bogie Frame Structure,” China Railway Science, vol. 39, pp. 98-103, 2018.
[9] Gao Y X, Wang X, Zou H, and Wang B J, “Load identification of bogie frame based on dynamic stress,” Journal of Mechanical Engineering, vol. 54, pp. 58-63, 2018.
[10] Wang S B, D. Burton, A. Herbst, J. Sheridan, and M. C. Thompson. “The effect of bogies on high-speed train slipstream and wake,” Journal of Fluids and Structures, vol. 83, pp. 471-489, 2018.
[11] Yang Y P, Jiang M X, Feng C Y, and Huang P, “Optimal design of railway freight car bogies based on finite element analysis,” Internal Combustion Engine & Parts, pp. 16-18, 2018.