Structural Performance of Subway Aluminum Alloy Car Body Analyzed by Abaqus Software

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Abstract. In accordance with the structural performance shortages of the lightweight subway, the verification of the strength and stiffness of subway vehicles is proposed. Then the load combination conditions are divided into 9 operating conditions based on EN12663-2010. With the aid of Abaqus software, the strength and stiffness are judged whether it is qualified. The experimental results show that the aluminum alloy car body structure of Shanghai Line 16 can meet EN12663 and TB/T1335. In this paper, it provides a verification process for the reliability of the strength and stiffness of subway aluminum alloy car body.

1. Introduction
Lightweight has been widely promoted in the rail-transit industry in recent years, especially in first-tier cities with high population density. The rail transit of Shanghai Line 16 operates at a speed of 100km/h, while the design speed is 120 km/h [1]. Thus, there is a great challenge to the integrity of the car body structure of Line 16 under high speed, heavy load and large-operating density [2].

In this study, strength and stiffness of the Shanghai Line 16 car body are analyzed by Abaqus software. Based on Section 5.4 of EN12663-2010 "Railway Applications-Structural Requirements of Railway Vehicle Bodies", the load combination conditions are divided into 9 operating conditions[3-5]. With the aid of Abaqus software, the stress and the deformation are obtained. According to the fourth strength theory, whether the maximum stress is less than the allowable stress. Stiffness analysis is mainly to judge whether the bending stiffness of the car body structure is more than 1.8×10⁹N·m².

2. Statics Simulation Analysis
In order to analyze the strength and stiffness of the complex car body structure, the car body model should first be simplified by Abaqus software. Through aligning the symmetry of the center line frame, a complete geometric model of the car body is obtained. In creating the boundary condition, step selects initial and the category selection is Mechanical: Displacement/Rotation. As shown in Table 1, the load combination conditions are divided into 9 operating conditions based on section 6.4 of EN12663-2010.
Table 1. The load combination conditions

| Load                   | Condition | Meaning                      |
|------------------------|-----------|------------------------------|
| Vertical               | 1         | Ready state                  |
|                        | 2         | Overcrowded state            |
| Vertical and Longitudinal | 3       | Tensile load in prepared state |
|                        | 4         | Tensile load in overcrowded state |
|                        | 5         | Compressive load in prepared state |
| Car lifting            | 6         | Compression load in overcrowded state |
|                        | 7         | One-position                 |
|                        | 8         | Two-position                 |
|                        | 9         | Three-position               |

For the regular and stress-dispersed middle structure in the aluminum alloy car body, a sparse shell element grid with a size of 50mm is used for discretization. For the window corners where the stress is more concentrated, a denser solid element grid with a size of 20mm is used. The welded structure is simulated by the element node coupling[6-8]. The number of units is 652 608 and nodes is 541 950, as shown in Fig.1.

![Fig. 1 The finite element model of the vehicle body (meshing)](image)

2.1. Strength Analysis

The sign of failure of the aluminum alloy car body is whether the structure has plastic deformation [9-12]. Section 5.4.1 of EN 12663-2010 mentions the allowable stress method for stress assessment [13-14]. This paper chooses the fourth strength theory to determine the established conditions and loads, and judges whether the strength of the car body structure is less than the material yield strength by the safety factor. The strength condition can be expressed as:

$$\sigma_f \leq [\sigma] = \frac{\sigma_m}{S}$$

In formula (1): $[\sigma]$ is allowable stress of material, $\sigma_m$ is yield strength of material. $S$ means safety factor, the value of $S$ is 1.15 from section 5.4.2 of EN 12663-2010.

2.2. Stiffness Analysis

Section 5.4.1 of EN 12663-2010 points out that the car body structure should ensure proper stiffness in order to avoid force response. The evaluation standard of car body stiffness is the equivalent bending stiffness of the car body structure, which can be calculated by the following formula (2):

$$EI = \frac{WL_i^2}{384\delta} \left( 5L_i^2 - 24L_2^2 \right)$$
In formula (2): \( EI \) is considerable bending stiffness; \( W \) means the vertical load per unit length; \( L_1 \) is vehicle fixed distance, 15700mm; \( L_2 \) is distance from bogie to car end, 3550mm; \( \delta \) is central deflection of car body underframe.

2.3. Discussion

Table 2 lists the yield strength of commonly material properties for aluminum alloy car body parts. Subsequently, the value of \[ \sigma \] can be calculated as following.

| Name       | Part                                       | \( \sigma_m \)/MPa | \( [\sigma] \)/MPa |
|------------|--------------------------------------------|--------------------|--------------------|
| 6005A-T6   | side wall, roof, underframe, end wall profile | 215                | 186.96             |
| 7020-T6    | traction, corbel, slow beam                 | 205                | 178.26             |
| 5083-T6    | 2-4mm thick aluminum plate                  | 115                | 100                |

Taking an overview of the results in figure and table, the discussions of strength and stiffness are as follows:

(1) In the case of the vertical static load, the maximum stress of the car body occurs at the operating condition 2. As shown in Fig.2, the maximum stress is 129.1 MPa and about 60.05% of corresponding material 6005A-T6 with the yield strength, which is less than the allowable stress of 186.96 MPa. The maximum deflection of 3.75mm occurs at the underframe under operating condition 2. After calculation, the bending stiffness of the car body structure is \( EI = 1.91 \times 10^9 \text{N}\cdot\text{m}^2 > 1.8 \times 10^9 \text{N}\cdot\text{m}^2 \).

(2) In the case of the combined vertical and longitudinal static load, the maximum stress of the car body occurs at 152.7MPa under the operating condition 6. As shown in Fig.3, it’s about 71.02% of corresponding material 6005A-T6 with the yield strength, which is less than the allowable stress of 186.96 MPa. The maximum deflection in the center of the chassis is 3.89mm under operating condition 6. After calculation, the equivalent bending stiffness of the car body structure is \( EI = 1.98 \times 10^9 \text{N}\cdot\text{m}^2 > 1.8 \times 10^9 \text{N}\cdot\text{m}^2 \).
(3) The 3-point support load is conducted to check safety of the car body structure during lifting. As shown in Fig.4, the maximum stress occurs at the operating condition 7, which is 144.7 MPa. And it is about 67.30% of corresponding material 6005A-T6 with the yield strength, which is less than the allowable stress of 186.96 MPa. The maximum vertical displacement of the car body occurs at 4.203 mm under operating condition 7. After calculation, the equivalent bending stiffness of the car body structure is $EI=2.14 \times 10^9\text{N} \cdot \text{m}^2 > 1.8 \times 10^9\text{N} \cdot \text{m}^2$.

3. Conclusion
In this study, strength and stiffness of the Shanghai Line 16 car body are analyzed by Abaqus software. The results show that the maximum stress under 9 operating conditions is less than the allowable stress, which meets EN12663. Additionally, the bending stiffness of the car body structure is greater than $1.8 \times 10^9\text{N} \cdot \text{m}^2$, which meets TB/T1335. Obviously, the aluminum alloy car body structure of Shanghai Line 16 can meet the strength and stiffness requirements. Therefore, aluminum alloy car body has a high application prospect in the field of urban rail transit system.

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