Structural Optimization of Subway Aluminum Alloy Car Body Analyzed by Optistruct Software

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Abstract. In accordance with the life cycle cost of the vehicle, the structure of the aluminum alloy car body structure of Shanghai Line 16 was optimized based on the Optistruct software. Then the load combination conditions are divided into 9 operating conditions based on EN12663-2010. Furthermore, the optimized car body is judged whether it is qualified. The experimental results show that the optimized car body structure of Shanghai Line 16 can meet EN12663 and TB/T1335. In this paper, it provides a high application prospect for reducing LCC of the aluminum alloy car body in the design stage.

1. Introduction
At high speed, heavy load and large-operating density, the integrity of the body structure is facing great challenges [1]. The optimization of the car body structure can not only ensure the safety in operation, but also improve the structure and reduce the waste of materials[2-3]. The overall performance of rail transit vehicles is improved on the basis of Life Cycle Cost (LCC), which is composed of procurement cost, energy cost, maintenance cost and recovery cost[4]. In order to improve the manufacturing process, the concept of Luther manufacturing has been imminent.

In this study, Optistruct software was used to optimize the aluminum alloy car body structure of Shanghai Line 16 based on Life Cycle Cost[5]. There is a discussion on whether the car body can achieve the specified static strength and stiffness after optimization. The optimal solution for each stage of the vehicle's life cycle is obtained, providing ideas for optimizing the design of the rail transit vehicle body structure.

2. Body Structure Optimization

2.1. Optistruct Optimization Process
The LCC of these materials is shown in Table 1 for the Shanghai metro vehicle. As for as the service life of the vehicle is 30 years, the stainless steel car is slightly better than the aluminum alloy car from the perspective of vehicle purchase cost and maintenance cost[6-7]. However, in terms of energy consumption costs and recycling costs, the aluminum alloy car body is significantly better than the weathering steel car and the stainless steel car[8-9]. Therefore, the aluminum alloy is used as the body. Additionally, on the premise of not reducing the stiffness and strength of the vehicle, optimizing the
structure of the vehicle body is the most effective measure to reduce the life cycle cost of the vehicle[10-12].

| Name                | Weathering steel car (ten thousand yuan) | Stainless steel car (ten thousand yuan) | Aluminum alloy car (ten thousand yuan) |
|---------------------|------------------------------------------|-----------------------------------------|----------------------------------------|
| Purchase Cost       | 420                                      | 490                                     | 700                                    |
| Energy Cost         | 315                                      | 297.1                                   | 283                                    |
| Maintenance Cost    | 242.5                                    | 211                                     | 220.8                                  |
| Recovery Cost       | -21                                      | -24.5                                   | -35                                    |
| LCC                 | 956.5                                    | 973.6                                   | 1168.8                                 |

In present work, the objective function is to select the overall mass of the car body as small as possible. The design variables are set to the thickness of each part of the aluminum alloy car body, and the constraint conditions are set to the optimized car body to meet the requirements of strength and rigidity. Optistruct software is used for structural optimization design, and the specific steps are shown in Figure 1. In Optistruct optimization, any convergence criterion can be considered to be convergent. When the objective function value of two adjacent iterations is within the target tolerance value, and the violation rate of the constraint condition is less than 1%, the calculation result is considered to be convergent. The calculation result is a local optimal solution due to the small changing range of each variable.

Figure 1. Optimization design flow chart of vehicle body Optistruct design
2.2. Optimization Model

2.2.1. Parameter Settings
In the optimization process of the aluminum alloy car body, the stress response is defined as stress and the mass response is defined as mass in Response. In the Optistruct software, the mass response is taken as a global response, which can affect the overall structure of the component at the same time. When the constraints are met, the car body mass parameters are made as small as possible. Compression load in overcrowded state is the worst working condition, and the size of this condition is optimized. The constraint condition is that the VonMises stress peak value of the car body structure should be less than the yield strength of the material 215MPa. Additionally, another constraint is that the deformation of the car body is less than 9.032mm of the original model.

In the Size Optimization: Design Variables interface of the Optistruct software, the parameters desvar and generic property are set. In view of the multiple thin-walled parts in the aluminum alloy car body profile structure, this paper sets 8 optimization variables. In the case that the initial value of the size optimization design is the original size of the car body, the size of the optimization variable should be guaranteed to be in the range of 1-8mm. The initial values of the eight optimization variables selected for the aluminum alloy car body are shown in Table 2.

| Num | Optimize variable parts (thickness) | Initial value (mm) |
|-----|------------------------------------|-------------------|
| 1   | Outer body cover                   | 3.5               |
| 2   | Car body inner cover               | 3.5               |
| 3   | The top cover of the car body      | 3                 |
| 4   | The lower cover of the top of the car body | 3           |
| 5   | Car body ribs                      | 2                 |
| 6   | Vertical ribs of car body          | 3                 |
| 7   | Bottom frame upper cover           | 3                 |
| 8   | Bottom cover                       | 3                 |

2.2.2. Optimization Results
Through the optimization calculation of the four iterative process, there are 8 convergent optimization results and the optimized car body mass. In order to meet the actual needs, it is necessary to round the optimized values of the design variables. The initial value of the variable and the optimized rounding value are shown in Table 3.

| Num | Number of iterations | Rounded value (nm) |
|-----|----------------------|-------------------|
| 0   |                      |                   |
| 1   | 3.5                  | 3.5               |
| 2   | 3.5                  | 3.32              |
| 3   | 3                    | 3.28              |
| 4   | 3                    | 3.11              |
| 5   | 2                    | 2.66              |
| 6   | 1.85                 | 2.66              |
| 7   | 2.35                 | 2.7               |
| 8   | 3.11                 | 2.7               |

As shown in Table 4, the decline of the body mass value in the objective function tends to be flat. After the fourth iteration, the result finally shows a state of convergence, and the optimization calculation can be considered complete. After the optimization, the body mass is reduced by 0.481t, which is 6% lower than the original body mass. The maximum deformation was reduced from 9.032mm to 8.853mm, a drop of 2%. The maximum stress is reduced from 152.7 MPa to 113.8 MPa, a
decrease of 25.5%. The optimized car body mass is reduced, and the maximum deformation and maximum stress are reduced to meet the strength requirements specified in the EN12663 standard. Therefore, the car body size optimization process is effective.

Table 4. Comparison of results before and after optimization under the most adverse conditions

| Condition                        | Parameter                  | Before optimization | After optimization | Percentage |
|----------------------------------|----------------------------|---------------------|--------------------|------------|
| Compression load in overcrowded state | Mass                      | 7.987               | 7.506              | 6%         |
|                                  | maximum deformation (mm)   | 9.032               | 8.853              | 2%         |
|                                  | Maximum stress (MPa)       | 152.7               | 113.8              | 25.5%      |

2.3. Strength and Stiffness Check

As shown in Table 5, the load combination conditions are divided into 9 operating conditions based on section 6.4 of EN12663-2010. Compared with the original model of the optimized aluminum alloy subway car body model, the optimized maximum Von-Mises stress value is less than the yield strength of the corresponding material. Therefore, the strength of the optimized aluminum alloy car body meets the requirements of the static strength regulations. Additionally, the maximum displacement after optimization is reduced, so the bending stiffness of the car body structure meets TB/T1335.

Table 5. The load combination conditions

| Condition                        | Maximum stress before optimization (MPa) | Maximum stress after optimization (MPa) | Maximum displacement before optimization (mm) | Maximum displacement after optimization (mm) |
|----------------------------------|------------------------------------------|-----------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Ready state                      | 90.59                                    | 59.16                                   | 2.632                                         | 1.913                                         |
| Overcrowded state                | 129.1                                    | 84.31                                   | 3.75                                          | 2.727                                         |
| Tensile load in prepared state   | 88.37                                    | 65.84                                   | 5.227                                         | 5.124                                         |
| Compressive load in overcrowded state | 132.6                                    | 98.76                                   | 7.841                                         | 7.687                                         |
| Compressive load in prepared state | 100.5                                    | 74.84                                   | 5.942                                         | 5.825                                         |
| Compression load in overcrowded state | 152.7                                    | 113.8                                   | 9.032                                         | 8.853                                         |
| One-position                     | 144.7                                    | 94.48                                   | 4.203                                         | 3.056                                         |
| Two-position                     | 111.3                                    | 72.68                                   | 3.233                                         | 2.351                                         |
| Three-position                   | 97.93                                    | 63.96                                   | 2.845                                         | 2.068                                         |

3. Conclusion

In this study, Optistruct software was used to optimize the structure of the aluminum alloy car body based on Life Cycle Cost. After five iterations, the weight of the optimized aluminum alloy car body was reduced from 7.987t to 7.506t, a weight reduction of 6%. Meanwhile, the maximum deformation of the optimized car body under the worst conditions is 8.853mm, and the maximum stress is 113.8MPa. The optimized body strength and stiffness meet EN12663 and TB/T1335. Therefore, the optimization results provide a high application prospect for reducing LCC of the aluminum alloy car body in the design stage.
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