Research on multi-condition topology optimization design of stainless steel spot welding vehicle considering weight coefficient

Yana Li\textsuperscript{1,a}, Di Meng\textsuperscript{2,b} and Zeyang Zhang\textsuperscript{1,c}

\textsuperscript{1}College of Locomotive and Rolling Stock Engineering, Dalian Jiaotong University, Dalian, Liaoning, China
\textsuperscript{2}Hangzhou Metro Operation Co., LTD, Hangzhou, Zhejiang, China
\textsuperscript{a}email: lyn1977522@163.com, \textsuperscript{b}email: mengdi0528@163.com, \textsuperscript{c}email: 987584322@qq.com

Abstract: A multi-condition topology optimization research method with weight coefficients is proposed to optimize the topological optimization of solder joints of stainless steel spot welding vehicle. Based on the SIMP variable density method, the compromise planning method, the orthogonal experiment design method, the gray correlation method, the entropy weight method and the analytic hierarchy process are used to introduce the weight coefficients, and objective function of the multi-objective topology optimization of the welding points of the stainless steel spot welding vehicle is established. This method realizes the topology optimization of the stainless steel spot welding vehicle model with the goal of flexibility the minimizing of multiple working conditions. It is concluded that the entropy weight method is more suitable for determining the weight coefficient analysis of objective function of multi-condition topology optimization. The average variation value of the flexibility under the three working conditions is the largest, and the number of solder joints is reduced by 17.8\% after optimization. The proposed multi-condition topology optimization research method can be applied to the topology optimization design of railway vehicle structure.

1.Introduction
In recent decades, topology optimization methods have been widely used in aerospace, materials, vehicles, machinery and many other fields. The evaluation of vehicle body structure performance needs to comprehensively consider multiple indicators. Therefore, multi-condition optimization is more in line with the actual engineering requirements for vehicle body research than single-objective optimization. The multi-condition function is used to consider the practicality and authenticity of the car body optimization problem as well as higher. When defining the objective function, the distribution of weight coefficients occupies a relatively important position in the optimization design. It reflects that the relative importance of the objective involves the allocation of the optimization objective and the evaluation direction of the objective function. If the setting is reasonable, the ideal optimization can be achieved. On the contrary, the expected effect may not be achieved or even mistakes may occur.

Therefore, judging from the current research status of scholars at home and abroad, most structural topology optimization is changing from a single-condition topology optimization problem to a multi-condition optimization problem, and the method of determining the weight coefficient of multiple conditions is no longer single. At present, many scholars in many fields have proposed different topology optimization methods to solve structural topology optimization problems.
optimization schemes. Yang, S. et al. [1] took the minimum weighted strain energy as the goal, set weights for typical operating conditions based on experience, and conducted a topology optimization design study on the commercial vehicle transmission housing; Gao, Y. et al. [2] obtained the weight coefficients through orthogonal experiments, took the local large stress area as the topological space, took the weighted flexibility as the objective function, and took the topological space quality score as the constraint condition to optimize the topological structure under multiple conditions; Qin, X. et al. [3] determined the weight of each evaluation index based on the entropy weight method, and performed multi-objective optimization on the automobile intake manifold; Fu, Y. et al. [4] established a multi-rigidity topology optimization model for the body structure of a mini-electric vehicle based on the analytic hierarchy process. The maximum weight stiffness of the body under multiple conditions is regarded as the optimization objective; Yuan, L. et al. [5] considered the collision conditions and used the analytic hierarchy process to determine the optimal weight coefficients under static multi-conditions, and carried out the multi-condition topology optimization design for the electric vehicle battery box. However, these studies rarely consider multiple working conditions and multiple methods to determine the topological structure optimization model of the weight coefficients at the same time, especially less applied in the railway vehicle structure.

Based on the SIMP density function interpolation model, this paper uses four different methods: orthogonal experiment design method, gray correlation method, entropy weight method and analytic hierarchy process to determine the weight coefficients in the objective function, and considered the weight coefficients on the stainless steel spot welding vehicle model researched the topology optimization of the stiffness of multiple working conditions.

2. Topology optimization method for multi-condition solder joints

For non-convex optimization problems, the traditional method of using the linear weighted sum method to convert the multi-objective optimization problem into a single-objective optimization which cannot ensure that all Pareto optimal solutions are obtained, while the compromise programming method can be a very good solution.

In the process of determining the objective function under multiple working conditions, each working condition corresponds to a weight coefficient. The traditional definition method usually gives an empirical values according to the designer's judgment of the importance of the working conditions which are only the designer’s subjective judgment not be accurate. When the number of working conditions is large, the designer cannot give the weight coefficient of each working condition. In order to solve this problem, this paper adopts orthogonal experimental design method[6], grey relational degree method[7], entropy weight method and analytic hierarchy process[8] to determine the weight coefficient in the objective function. The analysis process is shown in Fig.1.

Usually people turn the problem of maximum stiffness into the problem of minimum flexibility, that is, the minimum element strain energy. Therefore, the minimization of structural flexibility is taken as the objective function. In this paper, compromise planning method combined with power function can be used to obtain the objective function of multi-stiffness topology optimization.

\[
\min_{\rho} C(\rho) = \left\{ \sum_{k=1}^{m} \omega_k q \left( \frac{C_k(\rho) - C_k^{\min}}{C_k^{\max} - C_k^{\min}} \right)^q \right\}^{\frac{1}{q}}
\]

In formula (1); m is the number of calculation conditions; \(\omega_k\) is the weight value corresponding to the k-th working condition; q is the penalty factor, usually required q≥2. This article takes q=2; \(C_k(\rho)\) called the flexibility objective function of the k-th working condition; \(C_k^{\max}\) is the maximum value of the flexibility objective function of the k-th working condition, and \(C_k^{\min}\) is its minimum value.
3. Model establishment

3.1 The establishment of finite element model
Taking a stainless steel spot welded subway locomotive and car as the research object, the model is mainly composed of about 20mm four-node thin shell unit. The mass equipment unit is simulated by mass point unit, and the remaining mass unit is tiled on the floor plane of the car. Many parts of the vehicle are joined by solder joints. In the finite element model of the vehicle body, the total number of units is 2,440,828, and the number of nodes is 2,342,378, among which the total number of solder joints is 54,126.

3.2 The establishment of topology optimization model
According to the calculation of the static strength, the Von.Mises stress of all parts of the car body was lower than their allowable stress, and the safety factor of all parts of the car body was greater than 1.15. The static strength of the car body met the design requirements. In this paper, the topological optimization design of stainless steel spot welding car is carried out, and the topological optimization of welding spot layout is carried out for the spot welding unit with 6mm welding core diameter at the junction of sidewall and side beam of bottom frame. Taking the optimization design requirements into overall consideration, the optimization model is described as follows:

(1) Optimization objective: The flexibility value of the vehicle body is minimum in three working conditions (maximum vertical load, AW1+ longitudinal compression 980kN, AW1+ longitudinal tension 490kN);

(2) Constraints: The volume fraction is set to 70%;

(3) Design variables: optimize the relative density of regional solder joint units.
3.3 Calculation of weight coefficient

In this paper, the orthogonal test of three factors and three levels was selected for the working conditions. Each working condition, namely, each factor, was set with three level values, as shown in Table 1. Nine groups of schemes for the final experiment were obtained through assignment and normalization, and topology optimization was carried out in turn.

| number | case 1 | case 2 | case 3 |
|--------|--------|--------|--------|
| 1      | 0.4    | 0.35   | 0.25   |
| 2      | 0.5    | 0.2    | 0.3    |
| 3      | 0.4    | 0.4    | 0.2    |

The flexibility of each working condition is used as the comparison sequence in grey relational degree method and the original index matrix in entropy weight method. Through pairwise comparison of working conditions, the relative importance of pairwise comparison matrix is determined according to the level table of significance parameter definition of pairwise comparison matrix [9], and the weight comparison matrix in analytic hierarchy Process is obtained:

\[
A = \begin{bmatrix}
1 & 3 & 5 \\
1/3 & 1 & 3 \\
1/5 & 1/3 & 1 \\
\end{bmatrix}
\] (2)

Orthogonal experimental design method, grey relational degree method, and analytic hierarchy process are used to calculate the weight coefficients of the three working conditions of two-person seat in subway car corresponding to different methods, as shown in Table 2.

| number | methods                        | case   |
|--------|--------------------------------|--------|
|        |                                | case 1 | case 2 | case 3 |
| 1      | Orthogonal experimental design method | 0.381  | 0.381  | 0.238  |
| 2      | Gray relational analysis method                                         | 0.36   | 0.29   | 0.35   |
| 3      | Entropy method                                                            | 0.14   | 0.53   | 0.33   |
| 4      | Analytic Hierarchy Process                                                | 0.637  | 0.258  | 0.105  |

4. Results & Discussion

Because of the differences in weight coefficients, there are great differences in the comprehensive objective function. This paper proposes four methods to determine the weight coefficients of each working condition. The final optimization results of each objective function are shown in Table 3, and the method corresponding to the serial number in Table 3 is the same as that in Table 2, and the flexibility unit is N·mm.

In the optimization process, after 18 iterations, the objective function value decreases continuously and finally converges.

After optimization, each working condition of the flexibility reaches the minimum value. The flexibility value of method 4 corresponding to working condition 1 decreases the most. The flexibility values of method 3 corresponding to working condition 2 and condition 3 decrease the most. Based on the three working conditions, it can be seen that the flexibility optimization value of the optimization scheme corresponding to the weight coefficient determined by entropy weight method is lowest than
that of other methods, and the average flexibility change value of the three working conditions is the largest. In other words, the stiffness of each working condition is improved to a greater degree and the stiffness characteristics are better.

Table 3 Optimization results of objective functions corresponding to different methods

| number | Flexibility of each working condition |
|--------|-------------------------------------|
|        | case 1     | case 2     | case 3     |
| before | 5833886   | 2303723   | 2333296   |
| 1      | 5830025   | 2302113   | 2331223   |
| 2      | 5830204   | 2302159   | 2330826   |
| 3      | 5830463   | 2302076   | 2330750   |
| 4      | 5829902   | 2302232   | 2331450   |

After optimization, the solder joint distribution tends to be distributed at both ends. Fig. 2 shows the comparison of local solder spot distribution with 6mm core diameter before and after optimization.

![Before optimization](image1.png) ![After optimization](image2.png)

Fig. 2. Comparison of local solder spot distribution before and after optimization

After recalculating the static strength of the car body, the static strength of the car body increased but did not exceed the yield strength, and the position of the maximum static strength of the car body did not change significantly before and after optimization.

5. Conclusion

Taking the stainless steel welding vehicle model as the research object, four different methods were used to determine the weight coefficient of the objective function, and the topology optimization was carried out. The main conclusions are as follows:

1. Based on the variable density method, a multi-condition objective function topology optimization method was established by using the compromise programming method, which combines efficacy function with different weight coefficients on the importance of working conditions together.

2. Through the orthogonal experiment design method, the gray relation analysis method, the entropy weight method and the analytic hierarchy process, the weight coefficients of multi-condition optimization objective function were determined to avoid the weight ratio deviation which caused by the subjective factors of designers and improve the optimization model of multi-objective function.

3. After optimization analysis of the topology optimization model established by the four methods, it is concluded that the flexibility of each working condition is calculated to its target value, making the flexibility of the objective function closer to the minimum value.

4. Through comparative analysis of calculation results and change of flexibility values in various working conditions, topology optimization results of objective function method determined by the entropy weight method are better than those of the other three methods. Therefore, the entropy weight method is more suitable for determining the weight coefficient in the objective function of multi-objective topology optimization in structural topology optimization design. Furthermore the stiffness characteristics are not weakened and the static strength calculation still meets the standard requirements. After optimization, the number of solder joints with diameter of 6mm is reduced by 17.8%. This method can be applied to the topology optimization design of railway vehicle structure.
Acknowledgments
We would like to thank for the financial support of this work by Liaoning Provincial Department of Education Project (Grant No. LJKZ0497).

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