

Lightweight Design of Heavy-duty Logistics Robot Based on ANSYS

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Abstract: Based on ANSYS Workbench, this paper carries out static analysis on the three-dimensional model of the heavy-duty logistics robot frame established by CAD software, obtains the displacement and stress distribution of the frame, adopts the variable density method and the level set method to carry out topological optimization analysis of the frame, and makes structural improvement on the frame according to the optimization results. The static analysis of the improved model is carried out by applying the same load and fixed constraints as the original model. The results show that the weight of the improved model is 45% lower than that of the original model when the stiffness of the material is satisfied, and the lightweight of the heavy-duty logistics robot frame is realized.

Keywords: Rail Guide Vehicle(RGV); Topology optimization; Variable density method; Level set method; Light weight.

1. Introduction

With the development of artificial intelligence, the application of intelligent logistics in the heavy industry sector continues to increase. Intelligent logistics robots have emerged, enabling unmanned logistics operations and significantly improving logistics transportation efficiency. Among them, the Rail Guided Vehicle (RGV) plays an important role in intelligent warehousing, as it can easily connect with other logistics systems to achieve automation and is widely used in large-scale automated production workshops in heavy industries. The chassis, as the main load-bearing structure of the RGV, has a significant impact on stability when transporting heavy materials, leading to low positioning accuracy and excessive noise. Therefore, in the design of the chassis structure, in order to pursue stability, the thickness and weight of the chassis are greatly increased, resulting in high material costs. Currently, most designers optimize chassis materials based on design experience, but this design method is difficult to consider the overall performance of the chassis. In this paper, based on ANSYS Workbench, strength analysis of the RGV chassis is conducted. Under the premise of ensuring structural strength, topology optimization of the chassis is performed using the density method and level set method. The optimization results are used to improve the structure of the chassis, reducing the overall mass and providing a theoretical basis for the lightweight design of heavy-duty RGV chassis.

2. Static Analysis of RGV Chassis

The heavy-duty RGV is primarily driven by a four-wheel drive system, with two servo motors driving the front and rear wheels respectively. Material is retrieved from the material gantry by the lifting system and transported to the required

location along the laid-out track. The RGV chassis serves as the main load-bearing structure.

2.1. Establishment of Finite Element Model

The accuracy of the finite element model directly impacts the accuracy of finite element analysis, while the size of the finite element model directly affects the economy of the analysis [1]. Therefore, establishing an appropriate finite element model is crucial for finite element analysis [2].

The three-dimensional model of the chassis involves many structural features in the design process, such as chamfers, process holes, etc. These subtle structures have minimal impact on the overall strength of the chassis but significantly affect the establishment of the finite element model, leading to increased analysis time. Therefore, it is necessary to simplify these structures to some extent [3].

- (1) Ignore minor chamfers and non-structural process holes;
- (2) Remove components with minimal impact on chassis stress and deformation, such as dowel holes, bolt holes, bosses, etc;
- (3) Exclude components used for chassis decoration;

Key areas of Fig 1 and 3 are simplified according to the above requirements. Fig 2 and 4 depict the simplified models, and dimensional data after simplification are provided in Tab 1. The overall model is illustrated in Fig 5.

Table 1. Frame of simplified classis model

model parameter	Long /mm	Wide /mm	Base thickness /mm	Mass /kg	volume /mm ³
	2750	1490	100	2347.8	3.01*10 ⁸

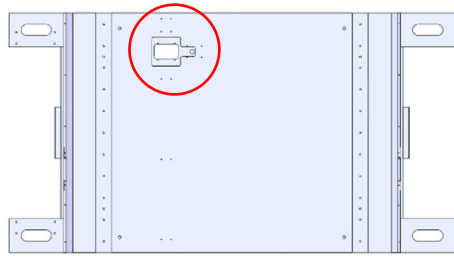


Figure 1. Front view of simplified front RGV frame



Figure 2. Front view of simplified RGV frame

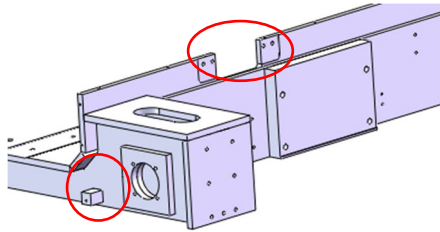


Figure 3. Side view of simplified front RGV frame

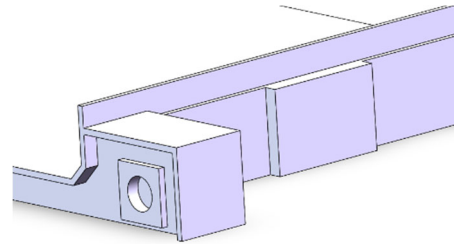


Figure 4. Side view of simplified RGV frame

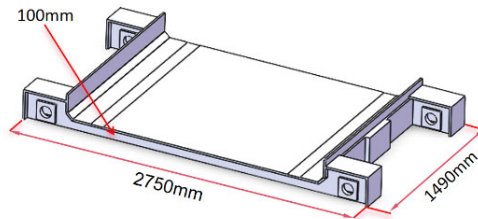


Figure 5. Simplified model

The size of finite element model meshes has a significant impact on computational accuracy, with smaller meshes resulting in higher precision [4]. However, during the meshing process, excessively small meshes can lead to long processing times or even meshing failure. When dividing the chassis model, irregularities necessitate segmentation within the Design Modeler tool in Workbench to approximate regular shapes (rectangles, circles) for each part, facilitating the creation of higher quality meshes. The model utilizes the Hex-dominant method for meshing the chassis, with a mesh size of 10mm and 5mm in stress areas, resulting in 1,500,194 nodes and 427,519 elements. The overall mesh quality is approximately 0.85, indicating good quality. The chassis structure employs Q345 material, with material properties detailed in Tab 2. Considering practical circumstances, a maximum safety factor of 2 is adopted.

Table 2. Q345 Material parameters

Material parameters	Poisson's ratio	Elasticity modulus /GPa	Yield strength /MPa	Density $/(g/cm^3)$
	0.5	206	345	7.85

2.2. Static Analysis

As the RGV vehicle travels at a constant speed along the track when transporting goods, the forces acting on the chassis are considered as fixed loads. These loads are applied and fixed constraints are imposed on the RGV chassis using the static analysis module in Workbench. Following software calculations, displacement and equivalent stress cloud maps for the RGV chassis are obtained, as shown in Fig 6 and 7 respectively.

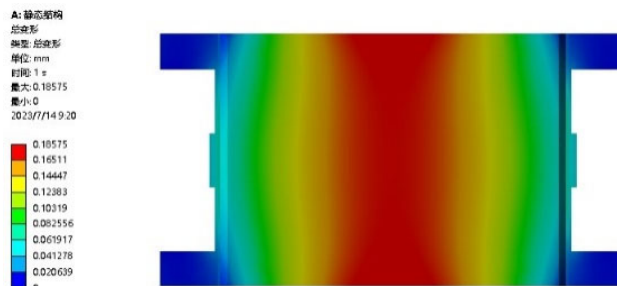


Figure 6. Displacement nephogram

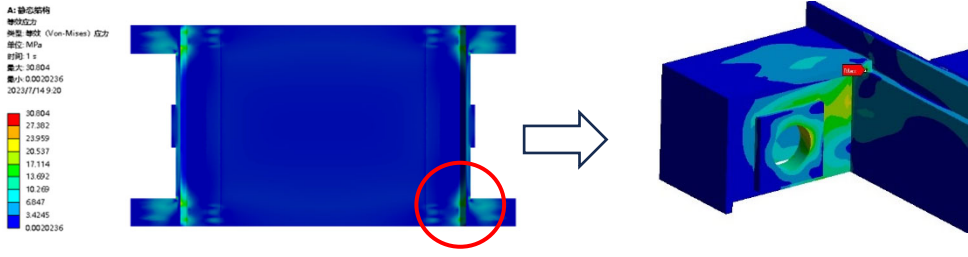


Figure7. Equivalent stress nephogram

Fig 6 indicates that the area of maximum deformation in the chassis is located at its central position. According to the computational results, the maximum deformation is 0.18575mm. Since the chassis is symmetrically structured, the deformation is symmetrically distributed along the centerline axis Fig 7 demonstrates that the maximum stress, calculated to be 30.804 MPa, is located at the connection between the wheel frame and the chassis, as indicated by the enlarged image. Calculations confirm that the maximum stress experienced by the chassis does not exceed the yield strength of the material, meeting the strength requirements. As depicted in Fig 7, the central stress within the entire chassis is relatively low, indicating significant margin in material strength and substantial room for improvement.

3. Topology Optimization Analysis

Topology optimization is a mathematical method for optimizing material distribution within a given design space based on specified loading conditions, constraints, and performance criteria. It is a form of structural optimization that falls into two main categories: continuum topology optimization and discrete structure topology optimization. Optimizing the distribution of materials falls under continuum topology optimization. Methods for optimization include density-based methods, homogenization methods, level set methods, etc. [5].

3.1. Topology optimization of the chassis based on the density method

The density method is the most commonly used optimization technique in topology optimization. It aims to optimize structures and minimize weight by modifying the distribution of material density [6]. The fundamental idea is to treat density within the structure as a design variable, with values ranging from 0 to 1, representing a continuous variable. During optimization iterations, the density distribution is gradually altered to achieve the optimal performance of the structure [7].

The optimization model for the density method is as follows:

Design Variables:

$$Find X = (X_1, X_2 \dots X_n)^T \quad (1)$$

Objective Function:

$$Min C(x) = F^T U = \sum_{i=1}^n f_i(x_i) u_i^T k_0 u_i \quad (2)$$

Constraints:

$$S. t. \begin{cases} V = \sum_{i=1}^n x_i v_i \leq f V_0 = V^* \\ F = KU \\ 0 < x_{min} \leq x_i \leq 1 (i = 1, \dots, n) \end{cases} \quad (3)$$

In the equations: X - Relative density of the elements; n - Number of design variables; F - Load vector acting on the structure; K - Global stiffness matrix; U - Global displacement vector; u_i - Displacement vector of an element; k_0 - Element stiffness matrix; $f_i(x_i)$ - Penalty function; V - Optimized volume; f - Material volume ratio; V_0 - Initial volume before optimization; V^* - Upper limit of volume; x_{min} - Introduced to avoid singularity in the stiffness matrix, typically set as $x_{min} = 0.001$.

In Fig 8, the blue area represents the topology optimization region, while the red area represents the loaded region, thus serving as an exclusion area. The remaining parts of the chassis are considered non-design regions and are not involved in the optimization calculations.

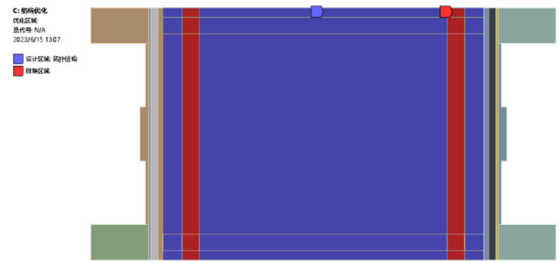


Figure 8. Design optimization area

The optimization objective is set to retain 50% of the original mass. Employing the density-based method for topology optimization, the heavy-duty RGV chassis model undergoes analysis. After 57 iterations, the optimized result model is depicted in Figure 9. Considering practical engineering requirements to prevent excessive deformation of the chassis under load, reinforcing ribbed plates are welded at the bottom of the chassis. Subsequently, the model is repaired and supplemented, resulting in a new RGV chassis model as illustrated in Fig 10.

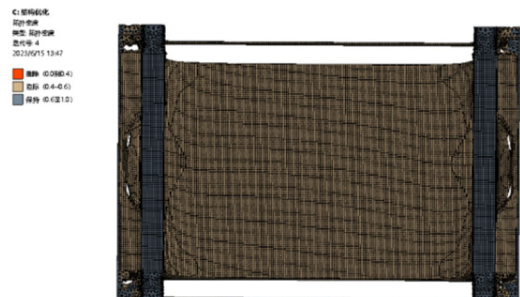


Figure 9. Topology optimization results based on variable density method

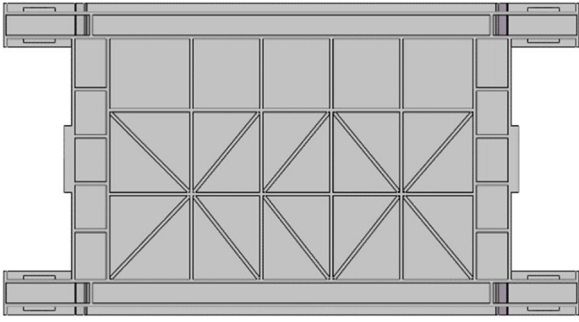


Figure 10. Supplementing the model based on variable density topology optimization

3.2. Topology optimization of the chassis based on the level set method

The level set method primarily achieves the evolution of the shape and topology of structures to obtain the optimal structural morphology. Its main idea is to regard the interface as the zero level set of a function in higher-dimensional space (referred to as the level set function), and the evolution of the interface is extended to this higher-dimensional space [8]. The level set function evolves and iterates according to the evolution equation it satisfies, with the zero level set

continuously changing. When the evolution of the level set tends to stabilize, the evolution stops, and the interface shape is obtained [9].

The optimization model, aiming to minimize structural compliance with the constraint of maximum volume under loading, is as follows:

$$\begin{aligned} \min: J(U, \phi) &= \int_V D\varepsilon(U)\varepsilon(U)H(\phi)d\Omega \\ s. t: \int_V D\varepsilon(U)\varepsilon(v)H(\phi)d\Omega &= \sum_i \int_D f_i v \delta(X - X_i) d\Omega \\ &(4) \\ \int_D H(\phi)d\Omega &\leq V_{obj} \end{aligned}$$

In the equations: V- Material region of the structure; U- Actual displacement; v- Virtual displacement; D- Elastic tensor; ε - Strain tensor; f_i -Concentrated force located at X_i ; V_{obj} - Volume of the target structure; $H(\phi)$ - Heaviside function of $\phi(X(t), t)$; $\delta()$ -Dirac delta function.

In Workbench, the optimization region is set to be the same as in the previous section. The optimization objective is to retain 50% of the original mass. For topology optimization, the "Level Set Method" is selected. After 52 iterations, the optimized result is shown in Figure 11. Following repair and supplementation, the new RGV chassis model is depicted in Figure 12.

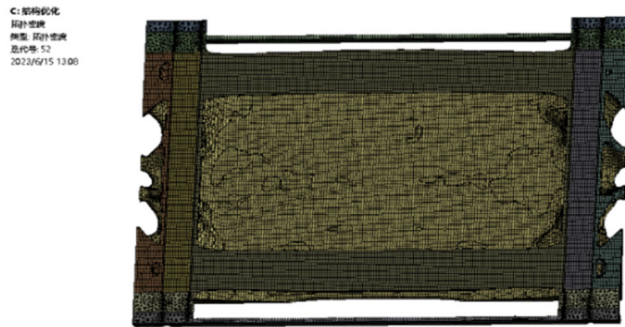


Figure 11. Topology optimization results based on variable level set method

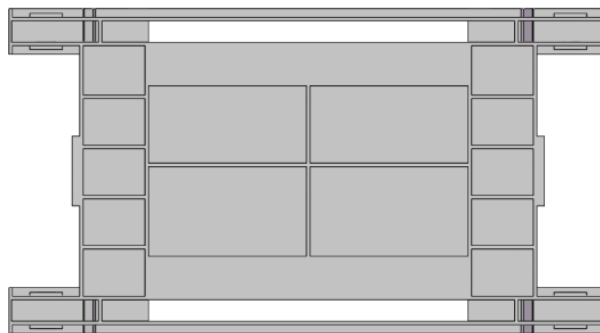


Figure 12. Supplementing the model based on variable level set topology optimization

3.3. Analysis of the optimized model

Applying the same loading and fixed constraints to the new models obtained through two different topology optimization methods [10], static analysis was conducted, and the results are presented in Tab 3.

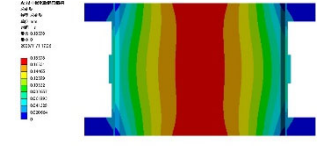
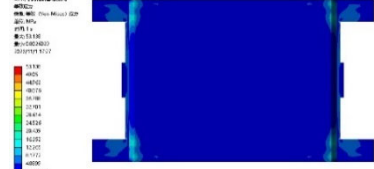
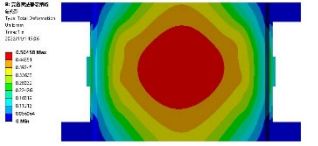
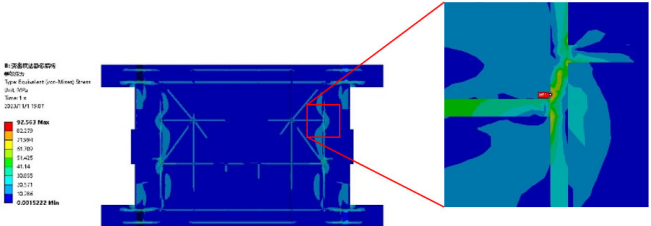
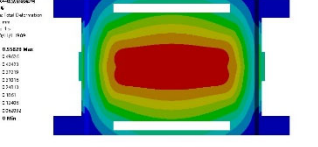
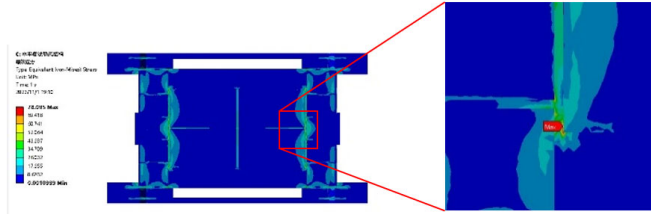
From the calculated results in Tab 3, it is observed that after topology optimization using the density method, the maximum displacement deformation of the heavy-duty RGV chassis is approximately 0.49275 mm, with the maximum displacement located at the center of the chassis, spreading

outward. The maximum equivalent stress is 51.933 MPa, located at the junction between the reinforcement plate and the main body of the chassis. Compared to the pre-optimized state, the maximum displacement increased by 0.301 mm, and the maximum stress increased by 21.129 MPa. Although there is a certain increase in both maximum displacement and maximum stress, they still meet the requirements for strength and stiffness. After topology optimization based on the level set method, the maximum displacement deformation of the chassis is 0.47754 mm, with the maximum displacement also located at the center of the chassis but spreading to the left

and right ends. The maximum equivalent stress is 75.167 MPa. Compared to the pre-optimized state, the maximum displacement increased by 0.292 mm, and the maximum

stress increased by 44.363 MPa, but they still meet the requirements for strength and stiffness.

Table 3. Comparison of optimization results

Optimization Methods	Maximum displacement deformation cloud map	Equivalent stress cloud map
Unoptimized	 <p>Max. displacement 0.18591 mm</p>	 <p>Max. stress 53.138 MPa</p>
Density-based	 <p>Max. displacement 0.50481 mm</p>	 <p>Max. stress 92.563 MPa</p>
Level set-based	 <p>Max. displacement 0.55829 mm</p>	 <p>Max. stress 78.095 MPa</p>

The comparison of model mass and volume obtained from two different optimization methods is presented in Tab 4. The model mass and volume reduced by 56.2% and 47.5%, respectively, when using the density-based method. Similarly,

the model mass and volume reduced by 47.5% when using the level set method. Both methods effectively reduce the mass of the new chassis.

Table 4. Comparison of quality and volume optimization results

Optimization Methods	Unoptimized	Density-based	Level set-based
Mass/kg	2347.81	1028.44	1232.94
Volume/(10 ⁶ m ³)	301.01	131.85	158.06

From the optimization results mentioned above, it is evident that both of the different topology optimization methods meet the condition of mass reduction. The models obtained from these methods exhibit displacement changes within the acceptable range after static analysis, and the maximum stresses are within the safety limits, meeting the design requirements. However, there are certain discrepancies between the chassis models obtained through topology optimization and the actual model. Therefore, it is necessary to repair and supplement the topology-optimized models to address issues such as installation positioning of other components and manufacturing feasibility. Comparing the two models mentioned above and considering the actual project requirements, the model optimized using the density-

based method is ultimately chosen.

4. Summary

(1) Based on the heavy-duty RGV chassis model, topology optimization using both density-based and level set methods shows that both methods effectively reduce the weight of the chassis.

(2) Considering the installation of other components on the chassis and the feasibility of chassis manufacturing, the chassis model optimized using the density-based method is suitable for engineering applications. Ultimately, the chassis weight is reduced by 46.2%, providing valuable guidance for RGV chassis design.

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