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Finite Element Optimization Analysis of the Frame Structure of the New Steel Mold Trolley

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In order to test whether the design of the new steel mold trolley meets the requirements of the working conditions, the ANSYS finite element simulation and optimization analysis of the frame system of the new steel mold trolley were conducted. After the analysis, the results show that the new steel mold trolley designed basically meets the requirements of strength and stiffness, but there are some problems of insufficient strength. Through the topology optimization of the gantry frame of the new steel mold trolley frame system, the "door shape" section gantry structure with better force structure was obtained.The influence of the specific structural parameters of the "door shape" cross-section gantry structure on the overall stress of the steel mold trolley frame system was studied. The results show that the optimized steel mold trolley gantry structure has a maximum stress of 174.94 MPa, an average stress of 26.22 MPa and a maximum deformation of 2.20 mm under the condition of extreme load, which can better meet the actual engineering needs.

Keyword: Steel mold trolleys, Frame system, Finite element analysis, Topology optimization

1 Introduction

Steel mold trolley is a special equipment to improve the surface quality and construction speed of tunnel lining and reduce the labor intensity [1-4]. Due to its strong applicability and easy operation, steel mold trolleys are widely used in transportation, pipelines, municipal, seabed, mine tunnel construction and other fields. Scholars at home and abroad have carried out rich and diverse research work on steel mold trolleys. Ma et al. used Midas/Civil design software to improve the design of a certain trolley, and analyzed its stress-strain and stability [5]. Peng et al. used Pro/E software and ANSYS software to study the design of the city opening cave-shaped steel mold trolley used in Xiluodu Hydropower Station, and analyzed the stress and strain of the trolley under different working conditions [6]. Cui et al. used ANSYS software to optimize and analyze the position parameters of the support rod in the gantry system of the trolley, it was found that the position of the support point has a significant impact on the distribution of structural stress and strain [7]. Liao et al. designed a steel mold trolley whose main structure can be used many times, which greatly reduces the cost of production [8]. Xu et al. carried out a lightweight design for a variable steel mold trolley, which reduced the weight of the trolley [9]. Although the structural optimization and mechanical property analysis of steel mold trolleys have done certain research work before, they basically stay in simple mechanical analysis, finite element method analysis rarely uses solid modeling, the calculation is relatively simple, and the structural optimization is mostly in order to achieve lightweight design for local minor repairs, and there is no specific parameter optimization design for the overall gantry structure, nor is it combined with actual engineering applications to make specific improvements in the design.

In this paper, the frame system of the new steel mold trolley is studied, the force analysis of the frame system is carried out, the structural optimiza design of the frame system is carried out with the cross-section topology optimization as the starting point, and the specific dimensional parameters are optimized in detail, so that the stress deformation of the new steel mold trolley under working conditions meets the design requirements [10].

2 Materials and Methods

2.1 The overall composition and features of the new steel mold trolley

In order to solve the problems of low work efficiency, low positioning accuracy, difficulty in dismantling the bottom mold, and safety hazards that occur in the practical engineering application of steel mold trolleys, we have designed several new types of

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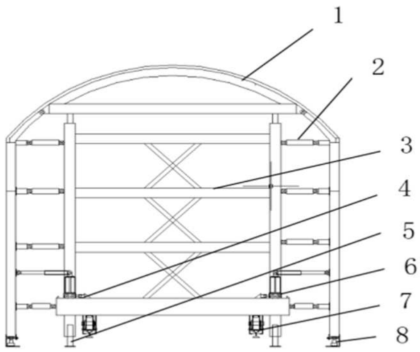
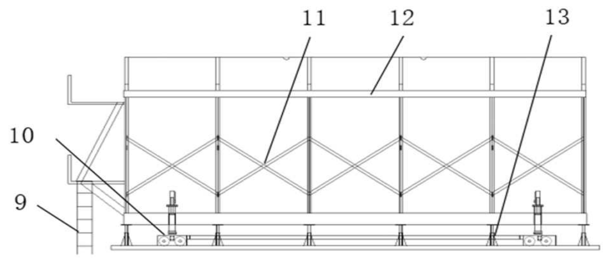
steel mold trolleys with different structures. The new slide rail self-propelled steel mold trolley is shown in Fig. 1, which is mainly composed of frame structure, formwork structure, hydraulic device of connecting mechanism and accessories [11]. Compared with the traditional steel mold trolley, its slide rail walking structure, as shown in Fig. 2 below, can realize automatic step change and improve the efficiency of slide rail laying [12]; At the same time, the fast dismantling bottom mold mechanism, as shown in Fig. 3 below, can quickly dismantle the bottom mold and solve the problem of secondary utilization of the bottom mold [13]; The laser positioning detection mechanism is designed for the new steel mold trolley, as shown in Fig. 4 below, which improves the operation accuracy and convenience of the steel mold trolley; The use of low-voltage distribution box control to ensure the normal operation of the steel mold trolley, reduce potential safety hazards, ensure the safety of staff, and improve the safety performance of the whole operation of the steel mold trolley [14].



a) Front view of trolley model



b) Left view of the trolley model

Fig. 1 *Structure diagram of the new steel mold trolley*

Where:
1…Formwork structure,
2…Connection structure,
3…Frame structure,
4…Hydraulic device,
5…Jacking device,
6…Left and right translation mechanism,
7…Slide rail walking mechanism,
8…Fast dismantling bottom mold mechanism,
9…Auxiliary devices,
10…Walking wheels,
11…Scissor support,
12…Crowd connecting beam,
13…Foundation jack.

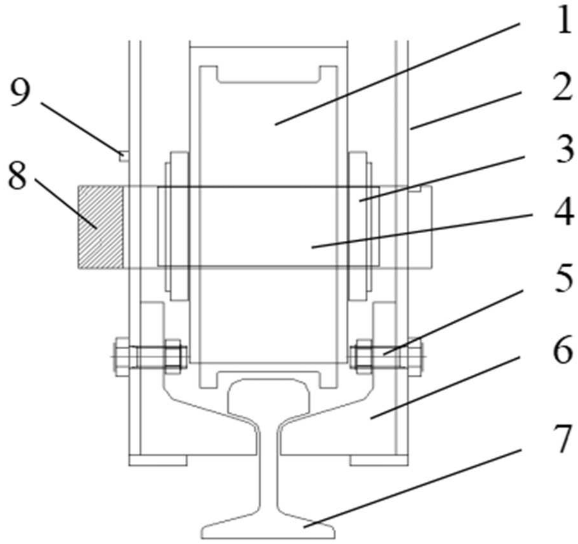


Fig. 2 *Schematic diagram of the sliding rail traveling device*

Where:
1…Wheel,
2…Baffle,
3…Washer,
4…Wheel axle,
5…Bolt nut,
6…Clamp block,
7…Walking track,
8…Electric motor,
9…Laser rangefinder.

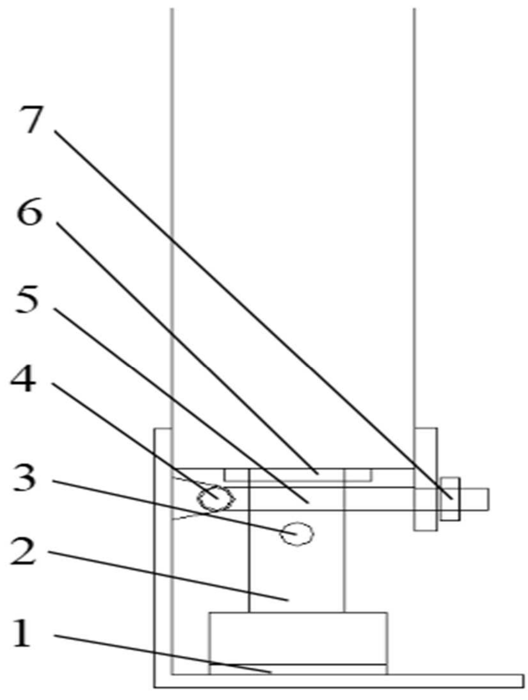


Fig. 3 *Fast dismantling bottom mold mechanism*

Where:
1…Movable baffle,
2…Large screw,
3…Jack hole,
4…Connecting key,
5…Small screw,
6…Fixing nut,
7…Connecting nut.

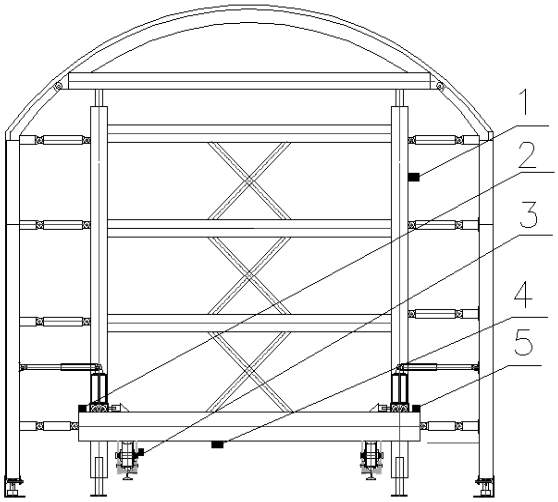


Fig. 4 *Schematic diagram of the installation of the laser positioning device*

Where:
1…Horizontal elevation laser positioning device,
2…Width ranging laser device,
3…Longitudinal laser positioning device,
4…Height ranging laser device,
5…Positioning and detectiondevice.

2.2 Load calculation of the frame of the new steel mold trolley

The forces on the steel mold trolley are mainly composed of the self-weight of the concrete, the side pressure and the self-weight of the trolley [15], and these forces are finally transmitted to the gantry frame through the supporting cylinders and jacks or horizontally or vertically. The gantry frame has become the most important structure for the steel mold trolley [16-17]. In order to ensure the quality and safety of construction, a force analysis of the gantry frame structure is required. During the analysis, according to the different forces of the new steel mold trolley in different construction stages, the load calculation is carried out by comprehensively considering the influencing factors of all aspects, compared with the load calculation method that only considers the self-weight of concrete and the self-weight of the trolley, the calculation results in this paper are more scientific and safe. Take the gantry frame structure system of the trolley as the analysis object as shown in Fig. 5.

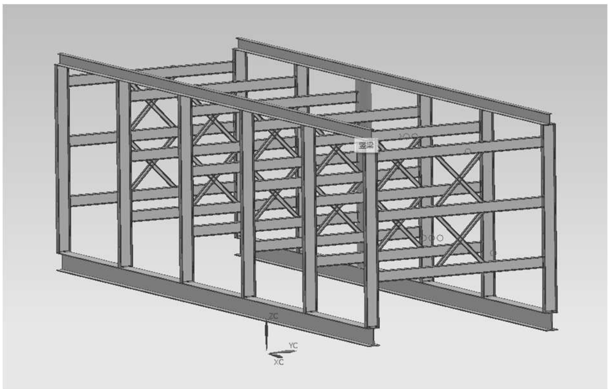


Fig. 5 *3D diagram of the frame structure of the trolley*

2.2.1 Calculation of pressure on the side formwork

According to the "Construction Structure Calculation Method and Design Manual", when the trolley is pouring the side wall, the gantry frame mainly subjected to the side pressure caused by the side formwork, and the maximum side pressure P1 of the newly poured concrete to the steel formwork is calculated according to the following formula [18,19].

$$P_1 = 0.22 R_c t_0 \beta_1 \beta_2 V^{\frac{1}{2}} \quad (1)$$

Formula, P1-concrete side pressure, kN/m^2; rc-gravity density, take rc=24.5 kN/m^3; t0-the initial setting time of newly poured concrete, h, take T0=5(h); β1-Correction coefficient for the influence of admixture, take β1=1.2;β2-Correction coefficient for the influence of concrete slump, β2=1.0;V-concrete pouring speed, take V=1.0 m/s. Therefore, the standard value of pressure on the plate side:

$$\begin{aligned} P_1 &= 0.22 R_c t_0 \beta_1 \beta_2 V^{\frac{1}{2}} \\ &= 0.22 \times 24.5 \times 5 \times 1.2 \times 1 \\ &= 32.34 KN/m^2 \end{aligned} \quad (2)$$

Effective head pressure height:

$$h = \frac{P_1}{r_c} = 1320\text{mm} \quad (3)$$

The standard value of horizontal load on vertical panels when pouring concrete P2=2.0 kN/m^2, and the standard value of horizontal load on vertical panels when vibrating concrete P3=4.0 kN/m^2, The load component coefficient of newly poured concrete on the pressure of the formwork side is 1.2; The load sub-coefficient of the load standard value when vibrating concrete is 1.4; When pouring concrete, the load sub-coefficient of the standard value of the load is 1.4. Considering the adjustment of the allowable stress of the old and new design rules, the design value of the steel formwork and its support is reduced by a factor of 0.85. After reduction, the horizontal load design value generated on the vertical panel when pouring concrete:

$$P_2' = 2.0 \times 1.4 \times 0.85 = 2.38 KN/\mathrm{m}^2 \quad (4)$$

Design value of horizontal load on vertical panels when vibrating concrete [20]:

$$P_3' = 4.0 \times 1.4 \times 0.85 = 4.76 KN/\mathrm{m}^2 \quad (5)$$

According to the load categories and numbering table and load combination table in the "Building Construction Manual", the side formwork strength is calculated for loads:

$$\begin{aligned} P_4 &= (P_1 \times 1.2 + P_3 \times 1.4) \times 0.85 \\ &= (32.34 \times 1.2 + 4 \times 1.4) \times 0.85 \\ &= 37.74 KN/\mathrm{m}^2 \end{aligned} \quad (6)$$

Lateral formwork stiffness calculated load:

$$\begin{aligned} P_5 &= P_1 \times 1.2 \times 0.85 \\ &= 32.99 KN/\mathrm{m}^2 \end{aligned} \quad (7)$$

In order to facilitate the analysis, the design values of side formwork strength and stiffness are uniformly adopted P4.

Due to the large verticality of the side formwork, it can be approximately regarded as a straight side wall for horizontal load calculation, and it is known that the length of the new trolley is 12 meters and the height of the side template is 4.312 meters, then F is:

$$\begin{aligned} F &= 4.312 \times 12 \times 37.74 \\ &= 1952.67 KN \end{aligned} \quad (8)$$

2.2.2 Load analysis of top formwork

When pouring concrete on the top formwork , the top formwork mainly bears the gravity of the concrete,and the concrete thickness is 0.7 m (including the over-digging thickness of 0.2m), and the pressure in the middle:

$$\begin{aligned} P_6 &= \mathrm{r_c s} = 24.5 \times 0.7 \\ &= 17.15 KN/\mathrm{m}^2 \end{aligned} \quad (9)$$

Since there is no exact theory to calculate the extrusion surface load, the design of the trolley needs to learn from similar structures and experiences at home and abroad [21]. Here refers to the parameter calculation provided by the Japanese company Qifu Industries, that is, the local extrusion surface load is:

$$P_7 = 47 KN/\mathrm{m}^2 \quad (10)$$

Maximum load on the top formwork:

$$\begin{aligned} P_S &= P_6 + P_7 = 17.15 + 47 \\ &= 64.15 KN/\mathrm{m}^2 \end{aligned} \quad (11)$$

The impact of cement is not considered here, and P6 is taken for calculation. The known surface area of the top formwork is: 86.12 m². Then the concretet self-weight of the op fromwork is:

$$\begin{aligned} G &= P_6 + S = 17.15 \times 86.12 \\ &= 1476.958 KN \end{aligned} \quad (12)$$

2.2.3 Self-weight of the trolley frame system

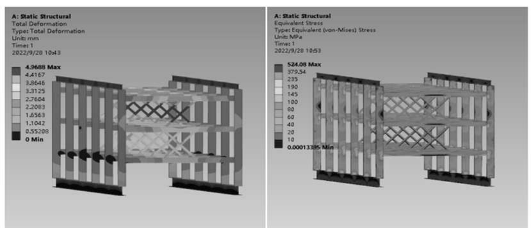
According to the actual size of the trolley design, a three-dimensional model of the 1:1 gantry system is established in UG, the volume of the model is 708400165.2577 mm³, and the material selected for the trolley gantry frame is Q235 steel, and the density is 7.85 g/cm³.So the quality of the trolley gantry frame is 5560941.29727g.The self-weight of the frame system is applied to all structural elements in the form of vertical downward gravitational acceleration.

3 Discussion of results

3.1 Finite element structure analysis and optimization of the frame system

3.1.1 Finite element structure analysis of frame system

First, a 3D model of the frame system was created in UG software and seamlessly imported into ANSYS Workbench. Considering the very large size of the frame model, and to ensure successful subsequent analysis, as well as to ensure the accuracy of the solution, the model needs to be appropriately simplified before the model is established [22]. After defining material properties, meshing, adding loads and constraints, solving and post-processing, the total deformation and equivalent stress clouds of the frame system were obtained. The results are shown in Figure 6 below.



a) Cloud map of total deformation b) Equivalent stress cloud map

Fig. 6 *The results of the cloud map of deformation and equivalent stress*

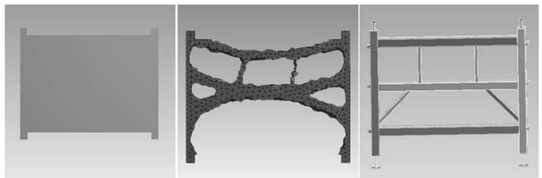
From the simulation results, it can be seen that the maximum deformation of the new trolley is 4.97 mm under working conditions. The local maximum stress was 524.08 MPa and the average stress was 41.87 MPa.

This equivalent force is greater than the yield strength of Q235 steel of 235 MPa, indicating that in some areas, this structure cannot meet the working strength of steel mold trolleys. The frame structure of the steel mold trolley needs to be further improved and optimized.

3.1.2 Optimization of the frame system

Due to the insufficient local strength of the frame system under operating conditions, Topology Optimization module from ANSYS Workbench is used to optimize the structural of the frame to find a structure that better meets the design requirements of the steel mold trolley. Topology optimization takes the optimization of material spatial layout as the starting point to realize the innovative design of structural configuration, breaks through the limitations of size and shape optimization, and has great advantages in structural weight reduction and full exploitation of potential load-bearing of the structure. The conceptual design using topology optimization method in the structural design of the new steel mold trolley can effectively reduce the blindness of the traditional empirical design method, improve the design efficiency and design quality, and provide an important reference for the innovative design of the new steel mold trolley structure to carry high performance under the premise of meeting the rigidity criterion [23].

The gantry substrate is modeled on the basis of the rectangle enclosed by the outer frame, and a cuboid area is removed at the bottom and top of the model, that is, to leave space for the sliding mechanism at the bottom and the beam above. A number of small and thin bumps were added to this substrate, as shown in Figure 7a, to facilitate the addition of loads and constraints to ANSYS Workbench. Here, the middle gantry with the highest stress was selected for analysis. After multiple reloads, constraints, meshing, and defining the optimization rate. The optimized results are shown in Figure 7b below. According to the topology optimization model, remodel and import it into ANSYS to obtain the optimized weight reduction model, as shown in Fig. 7c below.



a) Gantry substrate model, b)Model after topology, c)Optimized model

Fig. 7 *Optimization diagramof the frame*

Then, the mesh was divided, the load constraints were added, and deformation cloud maps and equivalent stress cloud maps are obtained after analysis and calculation. The distance between the vertical rod and the main rod and the angle between the oblique rod and the main rod are constantly adjusted, and the analysis results obtained are shown in Tab. 1 below.

Tab. 1 *Results after optimization*

distance between the vertical rod and the main rod (mm)	angle between the oblique rod and the main rod (°)	Total deformation (mm)	maximum stress (MPa)	average stress (MPa)
1200	45	20.1	455.59	43
920	45	2.6	331.2	36
1200	55	2.6	321	36
1200	60	4.5	303	38

According to the above table, the maximum stress of the initially optimized "door shape" frame section structure is 455.59 MPa, and the average stress is 43 MPa. After the initial optimization, the maximum equivalent stress has reduced 68.49 MPa, which is more reasonable than the previous "Scissor shape" section structure, but it has not fully met the design requirements of the steel mold trolley, and the deformation of the frame structure reached 20.118 mm, the middle structure still has the problem of uneven distribution, need to continue to optimize the structure. Finally, after analysis and comparison, when the distance between the vertical rod and the main rod is 1200mm, and the Angle between the oblique rod and the main rod is 60°, the most ideal formwork structure of the trolley is obtained. But the maximum stress is still too large, which does not meet the strength requirements. These excessively stressed places mainly occur in the middle of the bottom beam and the combination of some parts, as shown in Fig. 8.

To reduce the stress in these places, it is necessary to add enough reinforced ribs to the combined places to enhance local stability; Increase the thickness of double T-steel of the bottom beam to improve the extrusion resistance. The thickened and reinforced frame model is re-analyzed and calculated according to the finite element analysis process. The total deformation cloud map and equivalent stress cloud map of the new frame system have been obtained, as shown in the Fig. 9.

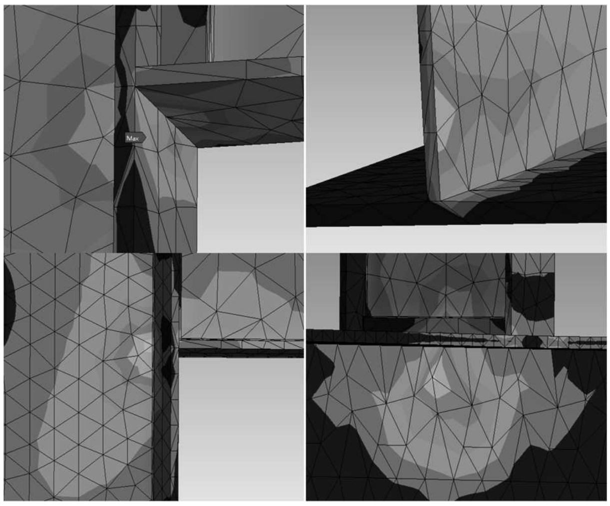
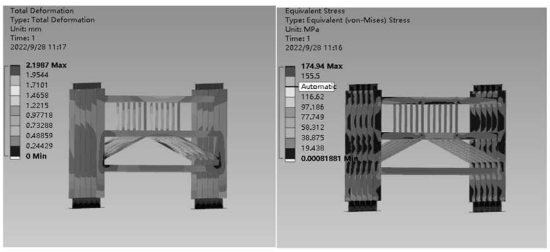
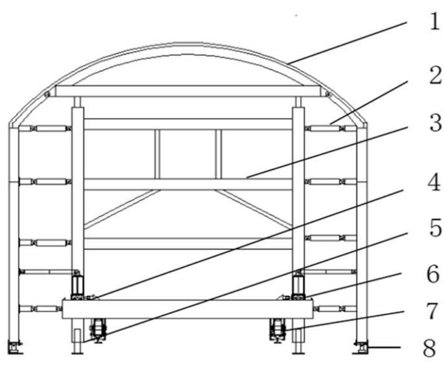


Fig. 8 *Location of excessive local stress*

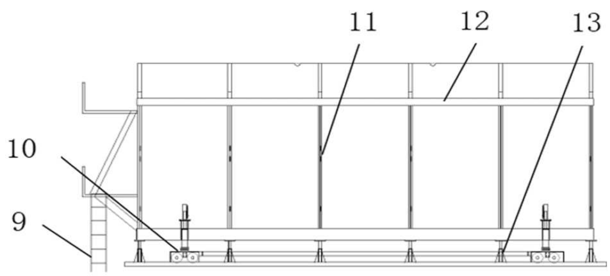


a) Cloud map of total deformation *b) Equivalent stress cloud map*

Fig. 9 *The results of the cloud map*



a) Front view of the optimized trolley model



b) Left view of the optimized trolley model

Fig. 10 *Structural diagram of the new steel mold trolley after optimization*

Where:
1…Formwork structure,
2…Connection mechanism,
3…Frame structure,
4…Hydraulic device,
5…Jacking device,
6…Left and right translation mechanism,
7…Slide rail walking mechanism,
8…Fast dismantling bottom mold mechanism,
9…Auxiliary devices,
10…Walking wheels,
11…Gantry-shape support,
12…Omnidirectional connecting beam,
13…Foundation jack.

The analysis of the cloud map results shows that the maximum deformation of the frame system is 2.20 mm, which meets the design requirements of the steel mold trolley with a deformation of less than or equal to 5mm. The maximum stress of the frame system is 174.94 MPa, which is less than the yield limit of Q235 steel. The average stress is 26.22 MPa, which meets the design strength requirements of the steel mold trolley. Referring to the optimization results, the drawing was re-drawn and the structural diagram of the optimized new steel mold trolley was obtained, as shown in Fig. 10.

4 Conclusion

Through the finite element analysis and calculation of the frame system of the new steel mold trolley, we can get the force of the frame system in the work. Based on the finite element analysis of the frame system, the main structure of the new steel mold trolley is topologically optimized, so we can draw the following conclusions.

The "door shape" section gantry structure is better than the "scissor shap" section gantry structure according to the topology optimization analysis.

The specific structural parameters of the "door-shape" section gantry structure (distance between the vertical rod and the main rod, angle between the oblique rod and the main rod, thickness of double T-steel and the reinforced ribs) are optimized. When the distance between the vertical rod and the main rod is 1200mm, and the Angle between the oblique rod and the main rod is 60 °C the overall force deformation of the frame structure is optimal.Under the ultimate load condition, the maximum stress is 174.94 MPa, the average stress is 26.22 MPa, and the maximum deformation is 2.20 mm.

According to the optimized structure, the optimized structure diagram of the new steel mold trolley was obtained, which can save the time and cost of trial production and experiment.

Acknowledgment

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