Optimization of a cantilever steel frame structure of bottom platform by finite element method

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Abstract. The finite element analysis of a cantilever steel frame structure of the bottom platform in civil engineering is carried out. Based on ANSYS and the basic characteristics of steel frame structure, parametric modelling is carried out, and the stress and deformation of the structure under extreme load conditions are analysed. The first-order optimization algorithm is used to optimize the beam cross-section size, which significantly reduces the total weight of the structure, thus providing a basis for the optimal design of the engineering structure.

1. Introduction
In the design of industrial buildings, warehouses, stadiums and ports, steel structures have become a major structural form, which has the advantages of lower cost, simple processing and manufacturing, and convenient transportation and installation [1, 2]. In order to further save steel and reduce costs, the total amount of steel used in steel structures needs to be well controlled [3-6]. Based on the engineering practice, the finite element method is used to analyze the cantilever steel frame structure of the bottom platform. The stress and deformation distribution of the structure are obtained, and then the structural optimization design is carried out.

2. Computational models
The bottom platform is a left-right symmetrical structure. According to the symmetry, the left part is taken for modeling and calculation. For the inverted cantilever steel frame structure of the bottom platform, the mechanical model of the steel truss structure is established and analyzed, and the load generated by the auxiliary mass such as the lifted member, the spreader, the keel and the patterned steel plate is applied to the steel truss structure to simulate the application of the load. The stress and deformation of the steel truss structure are obtained after the loads are applied. Then, the optimal design of the structure is performed based on the computational model.

The material of the frame structure is Q345-C steel. Bilinear hardening model is adopted for the steel. Material constants for Q345-C steel are as follows: yield stress: 350 MPa, elastic modulus: 210 GPa, Poisson's ratio: 0.3, density: 7850 kg/m³, linear hardening modulus: 2.1 Gpa.

According to technical performance requirements: single side maximum 10T vertical load and 7 or less staff, the 11T load is actually loaded when the calculation is performed. Since the exact position of
the load is undetermined and the load may move during the working process, the load is applied to the end of the cantilever platform in the worst case, and the calculation result is conservative compared with the actual situation.

The parametric model is established with ANSYS's APDL command stream. In the modeling process, the coordinates of the key points are first established, then the line is established according to the drawing, and finally the cross section of the beam is defined and the ID number is associated. For square tube 160 mm × 160 mm × 6 mm, section ID number is defined as 1; for 14a channel steel, section ID number is defined as 2; for 100 mm × 100 mm × 5 mm square tube, section ID number is defined as 4; for rectangular tube 100 mm × 50 mm × 4 mm, section ID number is defined as 5; for the rectangular tube 40 mm × 60 mm × 3 mm, the section ID number is defined as 7. The parameter definition for the cross section is shown in Fig. 1. According to the drawing the geometric model of cantilever steel frame structure of bottom platform is shown in Fig. 2.

![Parameter definition of channel cross section](image1)

(a) Parameter definition of channel cross section

![Parameter definition of rectangular tube cross section](image2)

(b) Parameter definition of rectangular tube cross section

**Figure 1.** Parameter definition of the cross section of the beam

![Geometric model of the steel frame structure](image3)

**Figure 2.** Geometric model of the steel frame structure
The steel frame structure is modeled using BEAM188 elements, and a total of 2941 elements are obtained. The finite element model showing the beam size is shown in Fig. 3. Parametric model with ANSYS's APDL command stream makes it easy to modify the model and optimize the structure.

![Finite element model of the steel frame structure](image)

**Figure 3.** Finite element model of the steel frame structure

### 3. Results and discussion

The Von Mises stress contour is shown in Fig. 4. It can be seen that the main beam of the bottom platform and the joint portion of the fixed part and the cantilever part have a higher stress level, and the maximum stress is 61 MPa, which is less than the yield stress of the material of 350 MPa. The deformation contour is shown in Fig. 5. It can be observed that the deformation near the end of the cantilever is larger, and the maximum deformation is 1.36 cm at the end.

The distribution law of the stress and deformation of the steel frame structure is similar with the cantilever beam. That is, the closer to the end of the cantilever, the larger the displacement and the smaller the stress; while the root of the cantilever (at the fixed end) has the smallest displacement and the maximum stress.

![Von Mises stress contour before optimization](image)

**Figure 4.** Von Mises stress contour before optimization

![Deformation contour before optimization](image)

**Figure 5.** Deformation contour before optimization
4. Structural optimization design

4.1. Process of optimization design

4.1.1. Basic element statement. Design Variables (DVS): Design variable parameters that need to be constantly adjusted during the design process. Each design variable may have upper and lower limits to specify the range of values for the design variables.

Here, dimensions $B_i$, $H_i$, $T_i$ ($i = 1, 4, 5, 7$) having a cross-sectional ID of $i$ and dimensions $B_2$, $H_2$, $T_2$, and $D_2$ having a cross-sectional ID of 2 are design variables. The upper and lower limits are taken as: the original value is added and subtracted by 50% of the original value.

State Variable (SVS): A variable parameter specifies the constraints that the design requires. It is a dependent variable of the design and a function of the design variable.

The equivalent Mises stress is taken as the state variable, and the maximum equivalent Mises stress is kept constant during the optimization process.

Objective Function: The variable parameter that is minimized in the design. It must also be a function of the design variable. Changing the value of the design variable will change the value of the objective function. In the ANSYS optimizer, only one objective function can be set.

Take the total volume $V_{\text{TOT}}$ as the objective function, and the minimum total volume is equivalent to the minimum mass. First-order optimization algorithm is used in optimization process.

4.1.2. Basic analysis process. Specify analysis files; declare optimization variables; select optimization tools or optimization methods; specify optimization cycle control methods; conduct optimization analysis; view design sequence results.

4.2. Discussion of optimization results

Keeping the maximum equivalent Mises stress value unchanged, the size of the cross section of the beam is optimized. The optimized design sequence obtained by the calculation is as follows, there are eight groups, of which the eighth group is the optimal design sequence. The relationship between $V_{\text{TOT}}$ and the optimized design serial number is shown in Fig. 6. The convergence of the optimized design can be observed. The stress and deformation contours after the optimized design are shown in Figs. 7 and 8, respectively.

The total volume of the cantilever steel frame before optimization is $1.4031$ m$^3$ and that of the cantilever steel frame after optimization is $1.2890$ m$^3$. With the maximum equivalent Mises stress unchanged, the total weight of the cantilever steel frame is reduced by 10.1% by optimizing the cross-section size of the beam.

However, it can be seen from Fig. 8 that the maximum deformation of the cantilever steel frame after optimization is $1.67$ cm, and the maximum deformation before optimization is $1.36$ cm. Therefore, the maximum deformation of the cantilever steel frame after the optimized design is increased by $0.31$ cm. If there is a requirement for stiffness, the maximum deformation of the platform can be taken as a state variable to satisfy the stiffness condition.

### Table 1. Section dimensions before and after optimization

| Variables | $B_i$/mm | $H_i$/mm | $T_i$/mm | $D_2$/mm | $V_{\text{TOT}}$/m$^3$ |
|-----------|----------|----------|----------|----------|---------------------|
| Before optimization | 160 | 160 | 6 | 140 | 6 | 9.5 | 100 | 100 |
| After optimization | 158.99 | 155.2 | 5.95 | 122.45 | 5.79 | 8.98 | 101.16 | 99.77 |

| Variables | $T_2$/mm | $B_5$/mm | $H_5$/mm | $T_7$/mm | $B_7$/mm | $H_7$/mm | $T_7$/mm | $V_{\text{TOT}}$/m$^3$ |
|-----------|----------|----------|----------|----------|----------|----------|----------|---------------------|
| Before optimization | 5 | 50 | 100 | 4 | 40 | 60 | 3 | 1.40 |
| After optimization | 4.92 | 46.0 | 92.69 | 3.60 | 39.56 | 59.0 | 2.93 | 1.29 |
5. Conclusion
The finite element model of the cantilever steel frame structure of the bottom platform is established from the engineering practice, and the stress and deformation of the steel frame structure under the limit load condition are analyzed. The analysis results show that the cantilever steel frame structure is safe. The first-order optimization algorithm is used to optimize the cross-section size of the beam, keeping the maximum equivalent Mises stress unchanged. Within the scope of the study, the total weight of the structure is reduced by 10.1%. The research method in this paper provides a reference for the design and optimization analysis of the cantilever steel structure.
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