Topological Optimization Design of the Gantry Steel Beam of the Simplified Freight Ropeway

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Abstract. Simplified freight ropeway are mostly built on high mountains and ridges inaccessible by roads, where the gantry of the ropeway needs to be handled manually. The traditional gantry with a single-piece weight of 63.9kg is hard to be handled manually. Based on the existing gantry structure, the single-piece lightest combined gantry construction is analyzed, and finite element analysis is conducted in this paper. After analyzing and calculating the steel beam of the combined gantry, it is determined that the weight of a single steel pipe and that of the steel bushing are 17.7kg and 30.5kg, respectively, which can meet the requirement in manual handling operation in steep terrain. On the premise of considering the cost and weight of the gantry, the H-shaped steel of different materials is determined to be selected for strength and stiffness analysis, and the H-shaped steel beam of Q345 material of 200mm×100mm×5.5mm×8mm is selected as the gantry for topology optimization design and finite element topology iterative calculation in this paper. The stress is distributed uniformly after optimization, and the mass of the steel beam of the H-shaped gantry is reduced from 63.9kg to 49.1kg, which meets the maximum single-lift load of 50kg for an adult man specified in GB12330-90 "the Limit on Carrying-load for Physical Work".

Keywords. Freight ropeway; Gantry; Steel beam; Topology optimization

1. Introduction

The gantry steel beam of the simplified freight ropeway is an important loading-bearing component in the freight ropeway project[1]. The gantry steel beam is used as a load-bearing beam to bear the weight of the steel cable to ensure that the steel cable is maintained at a certain height. Freight ropeways are usually built on plateaus and mountainous areas with complex environmental conditions and inconvenient mechanical transportation. The materials are often handled by manual work, which is difficult and labor-intensive. Most plateau regions have lush vegetation, and it takes a lot of time and money to pave the way for automobiles, which will cause damage to the vegetation on the mountains. In order to meet the requirements of strength and rigidity, two combined H-shaped steel beams are selected for the gantry steel beams of the simple freight ropeway, with a total weight of 127.8 kg, which is much heavier than the maximum single-lift load of 50kg of an adult man specified in GB12330-90 "the Limit on Carrying-load for Physical Work", and the regulations do not apply to plateau areas, mountainous region, muddy roads and roads with slopes greater than 10 degrees. Therefore, it is extremely difficult for being transported, and even cannot be transported to the designated location. At present, a method is urgently needed to reduce the weight of the gantry steel
beam and the multiple constraints of engineering applications shall be considered[2]. Based on finite element analysis and multi-objective constrained optimization, this paper studies the optimal design of lightweight gantry steel beams[3].

2. Simply supported beams model and analysis of traditional single H-shaped steel

The gantry of the simple freight ropeway is processed by H-shaped steel beams[4]. The gantry steel beam is used in the freight ropeway to support the pulling cable and load-bearing cables of the ropeway. It mainly bears the gravity of the pulling cable and the load-bearing cable, and has two load-bearing cables and two pulling cables respectively, which are applied at the position 1 meter away from the two ends of the gantry steel beam. The entire length of the beam L is 3m. \( F_1 = F_2 = 40000N \).

The stress analysis is conducted for simple-supported beam model of the H-shaped steel beam, to obtain the stress conditions of different sections, as shown in Figure 1-1:

![Figure 1. Simple supported beam model of gantry steel beam](image)

As shown in Table 1, the total weight of the H-shaped steel beams currently used is 127.8 kg, and the weight of a single piece is 63.9 kg. It is extremely difficult to handle it by manual work in mountainous areas. Without affecting the structural strength of the gantry, itself, this paper applies multi-objective constrained optimization to optimize the weight reduction of the gantry steel beam according to different transportation scenarios.

| H-beam Unit | Sectional area/cm² | Weight/kg | Maximum stress/MPa | Suitable material |
|-------------|---------------------|-----------|---------------------|------------------|
| 150×150×12×16 | 56.16 | 130.94 | 84.6 | Q345 |

The cost needed for the method introduced in this article is the lowest. It is necessary to comprehensively consider the price of the finished gantry on the premise that the maximum weight of a single adult man of 50kg as specified in GB12330-90 "the Limit on Carrying-load for Physical Work" is met[5].

Since the gantry steel beams need to be transported manually, and the excessive weight of a single gantry steel beam will cause extreme difficulty in transportation. In high altitude areas, the single load weight should not exceed 30KG, and the combined design to be used can greatly increase the weight of a single piece. Because it is difficult to combine I-beam and H-shaped steel, round steel pipes are used in this paper to construct the gantry steel beam in combined manner, which can be used to reduce the weight of a single gantry steel beam, but requires the highest cost due to the need for combined structural design. In order to meet the transportation needs on flat areas and low slopes, the topological optimization design is conducted based on the H-shaped steel beam in this paper.

3. Design and analysis of the lightest combined gantry

3.1. Selection of gantry shape

In high mountains and large ridges with a slope greater than 10 degrees, the gantry shall be designed to have the lightest single-piece weight without consideration of the cost of the gantry. As the materials are hard to be transported in some construction areas, and single H-shaped steel is heavier, a combined gantry steel beam can be considered to reduce the weight of a single gantry steel beam[6]. Since
H-shaped steel are difficult to be combined, round steel pipes are used to build the gantry steel beams. The comparison of the advantages and disadvantages of the round pipe combined gantry and the single H-shaped steel is shown in Table 2.

| Model | Outside diameter mm | Wall thickness mm | 3m single-piece weight kg | Maximum stress MPa | Suitable material |
|-------|---------------------|-------------------|----------------------------|---------------------|-------------------|
| 102×4 | 102                 | 4                 | 29.0                       | 688.7               | Q690              |
| 102×4.5 | 102              | 4.5               | 32.4                       | 621.4               | Q690              |

3.3. Static analysis of finite element of the combined gantry steel beams
In order to accurately simulate the stress of the gantry steel beam, the workbench module in ANSYS was used for finite element analysis. The combined steel beams are taken for analysis of four 83mm×3mm steel pipes. Analysis is conducted for the combined four 83mm×3mm round steel pipes, the same as the above operation, SolidWorks is first used for modeling. In order to fix the four round steel pipes, a 2mm steel bushing is used on the outside of the steel pipe for fixed connection, its model is shown in Figure 2.

Figure 2. Combined model of four steel pipes 83mm×3mm
The established model is imported into the workbench module of ANSYS software, to perform preprocessing work according to actual working conditions. In the actual project, the gantry steel beam is 3m long, and the force bearing points are located at two positions 1m away from the two ends. Then the supporting points are set at the two ends of the gantry for solution, to obtain the stress nephogram and deformation nephogram of the gantry steel beam, as shown in Figure 3-4.

![Figure 3. Combined stress distribution of four round steel pipes](image)

![Figure 4. Combined deformation quantity of four round steel pipes](image)

The stress distribution of the steel beam is obtained after finite element analysis. There are very few parts with stress concentrations in the gantry steel beam, with the maximum stress of 253.08 MPa, and maximum deformation quantity of 1.94 mm. The weight of a single steel pipe and that of a steel bushing in the combined gantry steel beam are 17.7kg and 30.5kg respectively, and they can be transported separately.

4. Calculation example of single H-shaped steel topology optimization considering cost and weight factors

The traditional H-shaped gantry requires the lowest cost, but it has a large design margin and is difficult to be transported. The combined gantry steel beams are used to greatly reduce the single-piece weight, and facilitate the manual transportation in the mountains and ranges, but greatly increase the material cost and manufacturing cost. The mass of the gantry steel beam with a size of 200mm×100mm×5.5mm×8mm is selected as the optimization target for optimization in this paper. The specific optimization steps of the gantry steel beam are as follows: First, the SolidWorks model of the basic shape that needs topology optimization is established according to the existing data of the gantry steel beam, to import the gantry steel beam model in basic shape into the topology optimization software. Setting is conducted in the topology optimization software according to the stress analysis of the gantry steel beam. The constraints, loads to be applied and material properties defined are added. Then, the optimization goal is set. Based on the safety requirement of the gantry steel beam, the topology optimization target is set to the maximum structural rigidity along with the remaining material mass percentage. A secondary modeling is performed according to the topology optimized structure. If the structure is reasonable and the weight is reduced, the topology optimization of the gantry steel beam is completed, otherwise, re-optimization will be performed.

The 200mm×100mm×5.5mm×8mm×3000mm H-beam is selected to build model in the 3D modeling software according to the static calculation results of a single H-shaped steel in this article. The ANSYS workbench is used to process the established geometric model, dividing the solid unit and the mesh[7]. Shape optimization in ANSYS workbench is selected and double-click for access. The steel beam model igs. file is imported under geometry. The meshing of the model is set in shape optimization and material properties, loads and constraints, etc. are added[8]. The working conditions of the gantry steel beam is selected as shown in Figure1.
The topological optimization of gantry steel beam can be used for solving the question by using mechanical concepts and optimization methods to meet design requirements. The purpose of topology optimization in this paper is to lighten the gantry steel beam[9]. The optimization plan of the gantry steel beam is determined according to the load distribution of the gantry steel beam, the loading position and the loading method. The area to be optimized and the percentage of material reduction shall be set in the optimized project. The percentage value of the material reduction will affect whether the model formed by the final optimization is available and whether the convergence result can be obtained[10]. After the meshing is divided and the load and boundary conditions are set, the solution under shape optimization is clicked on in the workbench for execution, and then the reduction percentage is modified several times to obtain different optimization results for comparison. The 30% material removal optimization is shown in Figures 5-6.

![Figure 5. The result of 30% material removal after topology optimization](image)

**Figure 5.** The result of 30% material removal after topology optimization

| Scope |
|-------|
| Scoping Method | Geometry Selection |
| Geometry | All Bodies |

**Definition**
- Target Reduction: 30.0%
- Suppressed: No

**Results**
- Original Mass: 65.574 kg
- Marginal Mass: 0.26355 kg
- Optimized Mass: 47.723 kg

![Figure 6. Topology optimization target and results of 30% materials removal](image)

**Figure 6.** Topology optimization target and results of 30% materials removal

The gantry steel beam with a 30% reduction in mass was remodeled according to the optimized results of 200mm×100mm×5.5mm×8mm×3000mm H-shaped steel beams. The removable part is removed, and the following model is obtained as shown in Figure 7.

![Figure 7. The optimized gantry steel beam](image)

**Figure 7.** The optimized gantry steel beam

The static analysis is performed on the model in Figure 7. The static structural module is selected in the workbench, to import the new model of gantry steel beam, complete the meshing division, and the material definition, meshing division and load application are conducted in turn, and then the solution is obtained through analysis[11]. After optimization, the maximum stress of the gantry steel beam is 510.9MPa, requiring the usage of high-strength steel for manufacture. Its weight is 49.1kg, and is reduced by about 23%, which can effectively reduce the transportation difficulty and meet the design requirements, as shown in Figures 8-9.
Figure 8. Stress distribution of the gantry steel beam after optimization

Figure 9. Deformation quantity of the gantry steel beam after optimization

Finite element model is established for 150-type H steel based on the study object of the gantry steel beam. Static analysis is carried out on the gantry steel beam with finite element software, and the analysis result was used as the theoretical basis for the topology optimization of the gantry steel beam structure. Through the topology optimization of the key components of the gantry steel beam, the removal of the material in some minor parts can reduce the mass of the steel beam successfully on the premises that the requirements of overall strength and rigidity is met.

Table 5. Comparison before and after optimization of gantry steel beam

| Gantry steel beam | Weight before optimization kg | Weight after optimization kg | Rate of change | Stress before optimization MPa | Stress after optimization MPa |
|-------------------|-------------------------------|-----------------------------|----------------|-------------------------------|-----------------------------|
| 200 H-shaped steel | 63.9                          | 49.1                        | 23%            | 217.3                         | 510.1                       |

It can be seen from Table 5 that after optimization, the mass of the steel beam is reduced to 77% of that before optimization. Meanwhile, the maximum stress born by the gantry steel beam after undergoing topology optimization has increased with the maximum stress increased by about 293MPa, of which the maximum stress is 510.1 MPa. The allowable stress range of Q550 H-shaped steel beam is 550 MPa. The maximum stress of the optimized structure is within this range.

5. Conclusions

According to the transportation characteristics of gantry steel beams in simple freight ropeway, three schemes of single-beam steel gantry, combined gantry and topology optimized gantry are analyzed, and the lightweight design of gantry steel beam in the simple freight ropeway is carried out. For steep terrain with large slopes where the weight of a single H-shaped steel is heavier, the combined gantry steel beams are used to greatly reduce the weight of a single gantry steel beam in this paper. Meanwhile, the topology of the gantry steel beam is optimized based on the H-shaped gantry high-strength steel beam with a size of 200mm×100mm×5.5mm×8mm in this paper. Through the lightweight design of the topological optimization of the key components of the gantry steel beam, the lightweight of the topologically optimized gantry steel beam is realized compared with that of the traditional H-shaped gantry steel beam requiring the lower cost than combined gantry steel beam on
the premises that the requirements of overall strength and rigidity is met.

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