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ISSN 2959-6157

Research on Structural Optimization Design Method of Truss

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Abstract:

Truss structure is widely used in the construction industry. The traditional optimization design methods mainly rely on the design experience of designers and lack of systematic theoretical support. This paper focuses on the structural optimization design methods of truss. In the first part, the optimization design methods of truss structure are introduced in detail from two main aspects: overall optimization and local optimization. Then, a specific case of top-supporting truss bridge is analyzed. The case is analyzed and opti-mized by the equivalent beam method in the whole optimization method. The result of case study shows that the truss structure can be optimized effectively by using the equivalent beam method with pier and analyzing the bending moment diagram. The equivalent beam method can be used to simplify and optimize complex structures. By dividing the various parts of the truss into beam-like segments and considering their interactions and stress distributions, an equivalent beam model can be constructed. This equivalent beam model captures the main mechanical characteristics of the truss while ignoring minor factors, thereby simplifying the calculation process. This paper can provide an effective reference for the optimal design of truss structure.

Keywords: Truss structure; Structure optimization design; Overall optimization; Local optimization.

1. Introduction

Truss structure is a lightweight structure composed of rods and joints, which has the characteristics of high strength, high stiffness and low weight [1]. It is widely used in construction, aerospace, bridge and mechanical engineering. With the continuous development of science and technology and the improvement of people's requirements on structural performance, the research on optimal design methods of truss structures has become more and more important [2, 3].

At present, many truss structure optimization design methods, such as topology optimization and shape optimization, require a high level of professional academic knowledge to be proficient in use, and many front-line designers do not have such in-depth professional academic knowledge. Therefore, these methods are usually only used by high-end or large-scale design unit staffs, while ordinary or small-scale design unit staffs only rely on their work experience when optimizing structures and lack theoretical support. The equivalent beam method greatly simplifies the calculation process by simplifying the complex truss structure into an equivalent beam model.This simplification makes the analysis more intuitive and easy to understand, while reducing the amount of calculation, improving the efficiency of the analysis, and compared with other optimization design methods, it only requires users to master basic subjects such as structural mechanics in civil engineering to be proficient in it. At the same time, the equivalent beam method can effectively handle a large number of design variables and constraints. By converting truss members into equivalent beam units, it is easier to apply various optimization algorithms and techniques to quickly find the optimal design solution that meets performance requirements. In addition, the equivalent beam method also plays a major role in saving materials. This method can judge and reduce the amount of materials by observing and adjusting the area of the bending moment diagram.

The research of optimization design methods is of great significance for improving the performance and efficiency of truss structures. Through optimization design, the lightweight, stiffness and strength of the structure can be improved. In addition, the optimization design method can reduce the time and resource consumption of repeated experiments and optimization processes and improve the design efficiency. For example, topology optimization methods, size optimization methods and multi-objective optimization methods combined with computer technology. This paper will first introduce some common optimization design methods for truss structures, then explain the equivalent beam method and demonstrate the optimization steps and optimization results of this method through an example of a truss bridge. Finally, the research conclusions of this paper can provide an effective reference for the optimization design method of truss structures.

2. Methodology

2.1 Truss Structure Optimization Design Method

2.1.1 Overall Optimization

The overall optimization is mainly in the aspects of material selection, construction parameters, structural layout, environmental factors, etc. taken into account. For example, choosing materials with adequate strength, stiffness and stability, depending on the application environment and thread storage requirements, can reduce material consumption and costs while improving the reliability of the structure [4]. The overall performance of the structure can be improved by adjusting key parameters such as the length of the bridge, the size of the section and the connection type, or by adding steel cables. Through reasonable selection of design parameters, the stress concentration and excessive deformation can be reduced, and the stability and bearing capacity of the structure can be improved. The overall performance of the truss can also be improved through reasonable structural layout. In the design, the symmetrical, regular and continuous structural form can be considered to improve the force distribution and stability of the structure. In addition, reasonable arrangement of support and reinforcement can improve the bearing capacity and stability of the structure. In the process of optimization, the impact of environmental factors on the structure should be considered. For example, when considering natural factors such as wind load, snow load, and earthquake, the adaptability of the structure can be improved. At the same time, considering the construction conditions and human factors can also improve the reliability and safety of the structure. In addition, the influence of economic factors on the structure can also be considered from the economic aspect. For example, under the premise of ensuring structural performance, engineering costs can be reduced by reducing material consumption and costs. At the same time, through reasonable maintenance and maintenance programs, the life and reliability of the structure can be improved, and the operating cost can be reduced.

2.1.2 Topology Optimization

Topology optimization is a design scheme that achieves the optimal design by adjusting the topology structure of

ISSN 2959-6157

the structure [2]. Firstly, a detailed finite element analysis is carried out on the structure of the truss, including the deformation, stress and strength of the truss, so as to determine the performance indicators of the truss [3]. Secondly, according to the performance index of the truss, the appropriate optimization algorithm is used to design the truss. For example, genetic algorithm, particle swarm optimization algorithm can be used to optimize the structure of the truss. Then, according to the optimization results, the structure of the truss is adjusted and modified, and further finite element analysis is carried out to verify the adjustment effect. If the results are not good, then further optimization design is needed. Finally, multi-condition verification should be carried out, for example, to check whether the stress concentration area meets the strength requirements, the degree to which the first-order buckling mode after optimization deviates from the original design, and other aspects of the optimization results.

2.1.3 Shape Optimization

This optimization method mainly focuses on changes in geometric shapes, such as curves, surfaces or cross sections [3]. By adjusting the geometric parameters, the shape can be more in line with the requirements. First, it is necessary to define the optimization objectives, such as improving the force transfer performance, stability or fatigue durability of the truss. Then design and prepare for different test schemes, such as selecting appropriate parameter ranges and determining parameters of optimization algorithms [5]. Next, the test data are analyzed and processed to extract useful information and evaluate the optimization effect. Moreover, according to the results of data, the design can be adjusted and improved to obtain a more in line with the requirements of the shape.

2.1.4 Size Optimization

By optimizing the size of the truss, the strength and stiffness of the structure are optimized, and its bearing capacity and deformation resistance are improved to achieve the purpose of optimization [6]. First, the objective should be determined, and the corresponding optimization plan should be formulated according to the objective. For example, adjusting parameters such as section size, shape and wall thickness should consider the actual situation and feasibility [7]. Then the optimization scheme is evaluated and optimized through computer simulation analysis. Numerical simulation methods such as finite element analysis can be used to analyze the structural properties in detail. According to the simulation analysis results, the optimization process is adjusted and improved, such as adjusting parameter values or changing optimization algorithms, so as to make the optimization effect more obvious and reliable [8].

2.1.5 Multi-objective Optimization

The multi-objective optimization problem involves multiple interrelated objective functions, and it is necessary to find a compromise solution to make multiple objectives reach the optimal state at the same time [5]. First, it is necessary to clarify the specific content of the optimization problem, including the objective function, constraints, design variables, etc. Then, according to the characteristics of the optimization problem, a suitable test space is designed to search for the optimal solution. Then the optimization algorithm is selected and the optimal solution is searched in the test space. At the same time, multiple objective functions need to be evaluated to determine the final optimal design scheme [9, 10]. Finally, the optimal solution is searched and evaluated, and the static and dynamic performance of the optimization results are verified through engineering verification using finite element software or joint simulation.

2.2 The Selection of Optimization Method

2.2.1 The purpose of choosing Equivalent Beam Method

First, the area of the bending moment diagram can reflect the overall bending moment distribution of the structure. The larger the area, the higher the bending strain energy stored in the structure, which usually means low material utilization efficiency. By reducing the area of the bending moment diagram, the internal force demand of the component can be reduced, thereby reducing the amount of material used. At the same time, the cross-sectional size of the component is usually determined by the maximum bending moment value. By adjusting the force transmission path to make the bending moment distribution more uniform or reducing the local peak moment, the overall cross-sectional size can be reduced while meeting the strength requirements. The equivalent beam method can achieve the purpose of optimizing design and saving materials by decomposing the complex structure into equivalent beam components and then optimizing its bending moment diagram.In addition, this method is simpler and easier to use than other optimization methods mentioned above. For example, topological structure optimization relies on iterative algorithms and finite element analysis, which require a lot of calculations for complex structures. At the same time, the optimization results may also produce complex geometric shapes of rods, which may lead to construction difficulties and increase costs.

2.2.2 The Theory of Equivalent Beam Method

The basic theory of the equivalent beam method is to convert complex components in the structure into equivalent beam structures, and use beam elements for simulation and analysis. This simplified processing method can effectively reduce the complexity of calculations while retaining the main deformation and stress characteristics of the structure. By converting the structure into a beam model, the shape and size can be optimized more conveniently to achieve the goals of light weighting the structure and saving materials. Meanwhile, the equivalent beam method greatly reduces the complexity of analysis by reducing it to an equivalent beam model, allowing designers to understand and optimize the truss structure more quickly and intuitively. This enables designers to find better design solutions in a shorter time and speed up product development. By using the equivalent beam method, designers can more accurately analyze the mechanical properties and force transmission paths of truss structures. This helps identify potential weaknesses in the structure and make targeted optimizations. Therefore, the truss structure optimized by the equivalent beam method often has better bearing capacity and stability.

2.2.3 The Optimization Steps style

The flow chart of optimization steps of equivalent beam method is shown in figure 1. The first step is structural decomposition which aims to decompose the complex structure according to the idea of beam model and decompose it into several equivalent beam components. The second step is model establishment. In this step, a beam element model needs to be established for each beam component, and beam elements are used to simulate its mechanical behavior, including stress characteristics and deformation characteristics. At the same time, according to the mechanical characteristics of the structure, the load and support force of each equivalent beam are calculated respectively, and the force diagram is drawn. Then, the internal force and deformation of each equivalent beam are calculated according to the force diagram, and the section size and material of the beam are determined. The optimization design of the truss structure is completed based on the optimization of the bending moment diagram. After the model is established, the bending moment diagram of the simple supported beam is drawn, and the area above and below the horizontal axis (that is, the amount of material) is optimized to minimize the bending moment diagram area. The next step is analysis and calculation. The beam unit model is used to conduct mechanical analysis and calculation of the structure to obtain the stress state and deformation of the structure. The last step is optimization design, which can optimize the shape, size and material of the structure based on the equivalent beam model to meet the design requirements and achieve the goal of lightweight design. In this paper, simulation platforms such as dinosap and structural mechanics solver were mainly used for analysis.

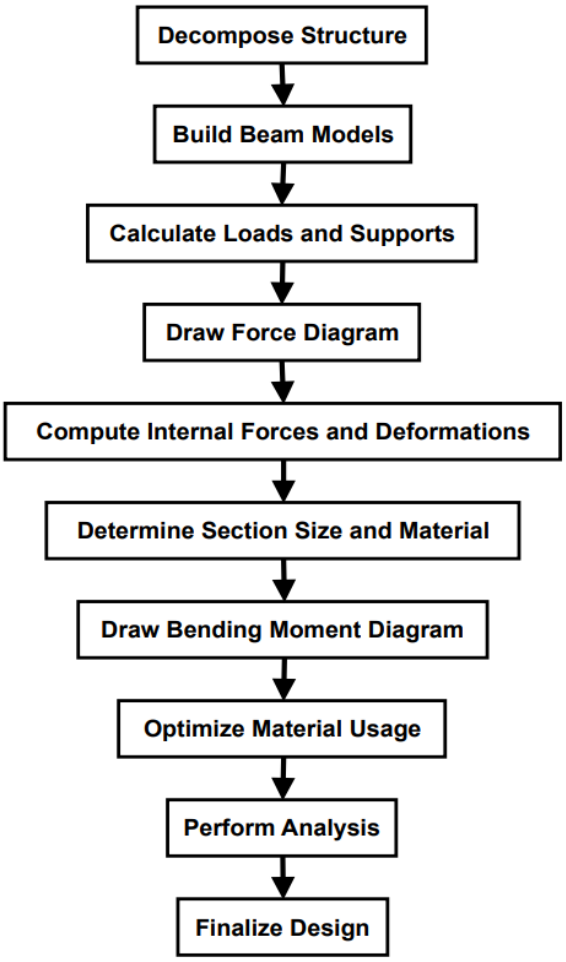

Figure 1: Optimization design flow chart.

3. Results and Discussion

3.1 Engineering Background

The bridge with truss structure is designed in this paper. As shown in figure 2, the total span of the bridge is 85 meters, 15 meters above the water level and 10 meters below the water level. The requirements are as follows: a complete space 5m high and 50m wide should be reserved under the bridge. In order not to affect the view, the truss is no more than 8 meters from the horizon. Based on this case background, this paper takes the minimum material consumption as the optimization goal, and carries out the overall optimization design of the truss bridge.

ISSN 2959-6157

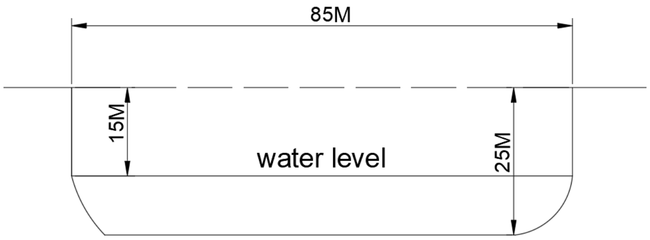

Figure 2: Background picture.

3.2 Optimization Results

According to the background and the specific design requirements of the bridge, the structural mechanics solver software is adopted. The top-supporting truss bridge designed before optimization is shown in figure 3. Figure 3 shows that the bridge has a total span of 90 meters and a height of 10 meters. Nodes 1 and 24 are fixed with two supports. The horizontal rods are each 5 meters long. A load of 562.50 KN is added to nodes 1 and 24 at the top, and a load of 1125.00KN is added to the remaining nodes. According to the overall optimization of the truss, the problem of whether to add piers under the bridge is deeply studied in this paper. Figure 4 is the upper bearing truss bridge designed after optimization. By optimizing the trusses in figure 3 by using the equivalent beam method, the optimized upper bearing truss bridge can be obtained, as shown in figure 4. As can be seen from figure 4, piers with a height of 10 meters were added at nodes 5 and 21 (where the piers were replaced by supports). The addition of piers will have a decisive effect on the bending moment diagram area of the subsequent simple supported beams. The remaining conditions are consistent with those in figure 3.

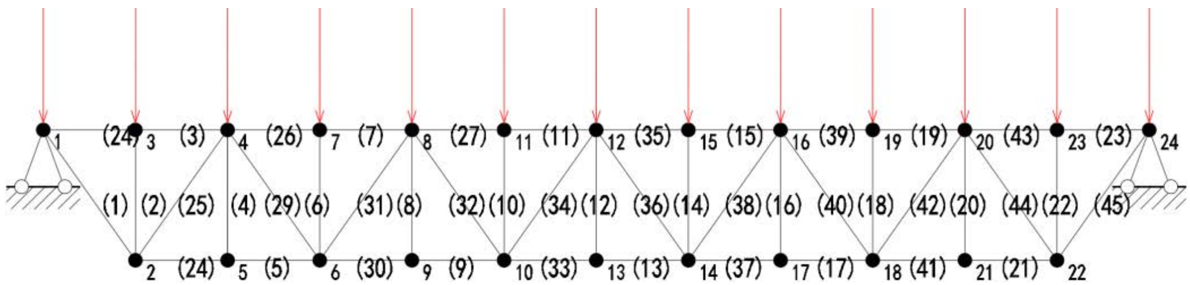

Figure 3: Optimization of front overhead truss bridge.

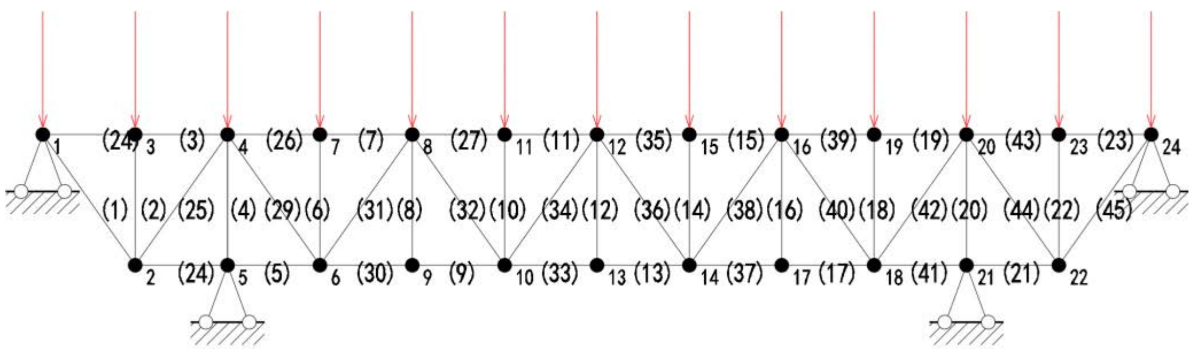

Figure 4: Optimized topside truss bridge.

The bending moment diagram of the simple supported beam is drawn on the computer by adding the corresponding load to each node of the simple supported beam with the structural mechanics solver. According to the area of the simple supported beam bending moment diagram, the material consumption of the truss bridge can be visually seen as shown in figure 5. In order to optimize the bending moment diagram of the simple supported beams of the front truss bridge, piers were not added. Figure 6 is the bending moment diagram of the simple supported beam of the truss bridge after adding the optimized pier. It can be seen from the diagram that the bending moment diagram area of figure 6 is significantly smaller than that of figure 5.

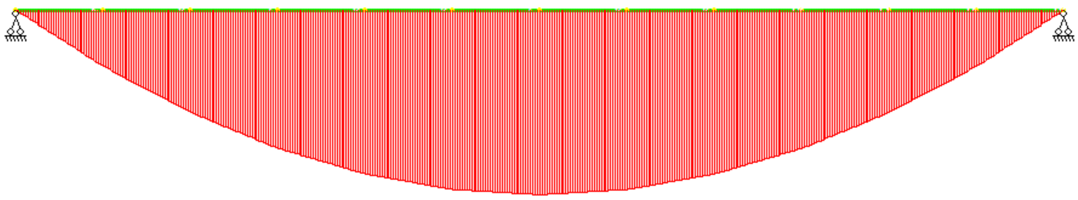

Figure 5: Bending moment diagram of simply supported beam before optimization.

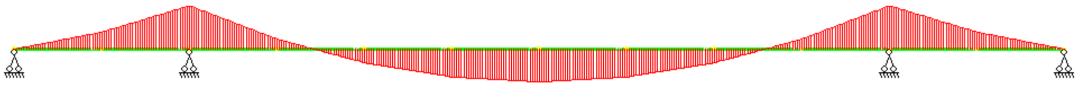

Figure 6: Bending moment diagram of the simplified beam after optimization.

3.3 Discussion

Table 1 shows the data analysis before optimization of the top-bearing truss bridge. The struts are divided into end A and end B. After analyzing the axial force, section side length, section bearing capacity, rod length and volume of the struts, the volume summing is finally done.

Combined with figure. 2 and figure 3, the area of front and rear bending moments of the truss bridge is optimized. The optimal design of truss structure by using the equivalent beam method greatly reduces the total material consumption of the member. It shows that the equivalent beam method can simplify the calculation process, reduce the calculation amount and improve the analysis efficiency in truss optimization. In the study, the equivalent beam method deals with a large number of design variables and constraints more efficiently. By converting the truss members into equivalent beam elements, the optimal solution to meet the performance requirements is quickly found. Moreover, in this topic, the design of piers is necessary, and in order to reduce the amount of materials, triangular conical piers can used. The use of piers on the role of the amount of materials is decisive. The model of the bridge adopts the design of an upper bearing bridge to minimize the presence of pressure rods, so as to maximize the role of each truss. By adjusting the overall layout of the truss, material savings can be achieved. For example, research on the Chongqing East Railway Station project has shown that the displacement in the middle of the truss is greatly affected by bending moments and shear forces. Reasonably reducing the span or height can reduce deformation requirements and thus reduce material usage. In addition, by using multi axis additive manufacturing technology to synergistically optimize the layout and construction direction of the truss, the increase in material volume can be reduced compared to traditional three-axis printing while satisfying the suspension angle constraint.

Table 1: Data analysis of the truss bridge.

Bar member	Terminal A	Terminal B	Axial force (N)	Section side length (m)	Section bearing capacity (N)	Rod length (m)	Volume (m^3)
1	1	3	3113.05884	0.089614117	25000	7.5	0.06023
2	3	4	3113.05884	0.089614117	25000	7.5	0.06023
3	4	7	233.8018	0.103406093	25000	7.5	0.080196
4	7	8	233.8018	0.326998746	25000	7.5	0.801961
5	8	11	3153.12002	0.01	25000	7.5	0.021929
6	11	12	3153.12002	0.01	25000	7.5	0.021929
7	12	15	3165.04185	0.01	25000	7.5	0.021929
8	15	16	3165.04185	0.01	25000	7.5	0.021929
9	16	19	198.03633	0.112356353	25000	7.5	0.09468
10	19	20	198.03633	0.112356353	25000	7.5	0.09468
11	20	23	2980.80216	0.091580566	25000	7.5	0.062903
12	23	24	2980.80216	0.091580566	25000	7.5	0.062903
Volume summation							1.405499

ISSN 2959-6157

4. Conclusion and Prospect

This paper mainly studies the optimal design method of truss structure and draws the following conclusions:

(1) This paper takes a practical case as the engineering background to carry out the overall optimization design of the truss structure. The optimized design structure shows that: The equivalent beam method can be used to optimize the design of the upper truss structure. The area of the bending moment diagram of the simple supported beam is greatly reduced by adding pier at the appropriate joint position of the truss bridge model. The size of the bending moment diagram of the simple supported beam of a truss bridge can directly reflect the amount of materials required for bridge design. Therefore, in the optimal design of bridge, the optimization of the whole bridge can be realized through the optimization of the bending moment diagram of the simple supported beam.

(2) The equivalent beam method makes a significant contribution to bridge optimization. As a complex spatial structure, analysis and optimization of bridges requires a large amount of calculations and variables. Equivalent to the beam method, it is simplified into a bridge model, which reduces the complexity of analysis and speeds up optimization. Compare with traditional methods, it reduces optimization indicators and improves optimization efficiency, allowing designers to find high-quality solutions faster. This method can accurately analyze the mechanical performance and force transmission path of the structure, identify defects and optimize them, thereby improving the structural load-bearing capacity and stability.

(3) This study uses the equivalent beam method to simplify the truss structure into a beam model for analysis and optimization. However, this method ignores characteristics such as node stiffness and component interaction, which may lead to errors when applied to actual design and affect performance prediction. For complex or irregular trusses, the equivalent beam method is limited and difficult to accurately capture dynamic effects.

(4) Intelligence is an important trend in future truss optimization, relying on intelligent algorithms and optimization software. Besides, new materials, such as carbon fiber composite materials, will improve the performance of trusses and realize intelligent functions as well. At the same time, the concept of sustainable development will promote truss optimization to pay more attention to environmental friendliness and sustainability. In addition, the optimization of truss material usage still needs to be promoted in a coordinated manner from the overall layout and local components, combining intelligent algorithms, construction process innovation and new material applications to break through the limitations of traditional design methods. Future research should also focus on multidisciplinary cross-cutting, such as introducing quantum neural networks into structural optimization to further improve the efficiency of solving complex problems.

Acknowledgements

This article has no sponsorship.

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Appendix

All the authors contributed equally and their names were listed in alphabetical order.