Research Progress and Application Analysis of Mechanical Performance Optimization Design of Truss Structures

Zimeng Zhang
Jinan New Channel -JUTES High School, Jinan, Shandong, China

Abstract: Truss structures are widely used in buildings, bridges and other engineering fields due to their efficient bearing capacity and economy. With the increase in the scale and complexity of truss structure design, traditional design methods have gradually exposed problems such as low efficiency and insufficient precision. Optimization design, as an effective way to improve the mechanical properties of truss structures, has gradually become a research focus. This paper reviews the basic theories, methods and applications of mechanical performance optimization design of truss structures, introduces the limitations of traditional design methods and the application progress of modern optimization algorithms. Intelligent optimization methods, such as genetic algorithms and particle swarm optimization algorithms, can effectively handle complex optimization problems with multiple objectives and multiple constraints, and improve design accuracy and efficiency. At the same time, the integration of new materials and interdisciplinary technologies provides a more advanced solution for the optimization design of truss structures. This paper also discusses the application cases of truss structure optimization design in actual engineering, and analyzes the actual effects of different optimization methods and the challenges they face. In general, the research on truss structure optimization design not only promotes the performance improvement of truss structures, but also provides theoretical support for the sustainable development of engineering construction.

Keywords: Truss Structure; Mechanical Properties; Optimization Design; Intelligent Algorithm; New Materials

1. Introduction

The truss structure is widely used in the engineering fields of bridges, buildings, and towers due to its efficient mechanical properties, light weight, and strong bearing capacity. In the process of continuous changes in modern engineering needs, especially under large spans, complex environments, and high-strength conditions, higher requirements are put forward for the design of truss structures. Traditional design methodologies for trusses proved successful in some small and simple structures but mostly disclosed such problems as great volume of calculation, low precision, and insufficient efficiency when used to deal with complex structure engineering. Therefore, improving the design efficiency of a truss structure, optimizing its mechanical properties, and reducing the engineering cost have been an important issue in today's engineering field.

Then the research of truss structure optimization design came into being, which optimally selected the size, material, and geometry of its components to achieve the optimum performance of the structure. On the condition of satisfying such constraints as bearing capacity, stability, and deformation, optimization design can reduce the structural weight with minimum consumption of materials. It will do so while effectively improving structural economy and sustainability. Presently, since the development of computer technology, those defects of traditional optimization methods appear gradually. The introduction of intelligent optimization algorithms and intelligent materials gives a new perspective and approach for the truss structure optimization design. Accordingly, the intelligent optimization approach has the ability to explore globally for the best in a wider design space. This brings new opportunities into truss structure designs. Therefore, the research on the optimization design of truss structure mechanical properties has great significance not only in improving the accuracy and efficiency of engineering design but also in promoting the development of engineering technology in a more intelligent and sustainable direction.

2. Basic Theories and Methods for the Optimization Design of Truss Structures

2.1 Mechanical Performance Analysis and Traditional Design Methods of Truss Structures

The truss structure has been widely applied in such projects as bridges, buildings, high-rise towers with the characteristics of effective bearing and lightening the structure. Normally, the analysis of mechanical performance of a truss structure is divided into two parts: statics and dynamics. Static analysis is used mainly for the internal force calculation of each component in the truss, node force and axial force of rods included, to make the truss keep balance under the action of external load. The dynamic analysis will pay much attention to response behavior with dynamic load such as vibration or wind load caused by an earthquake. And the design method of truss is mostly based on static principles conventionally. The size and material for each component are determined through the solution of the mechanical equations of the rods. Among usually adopted analysis methods, the FEM and classical analytical method-like force method and displacement method-find wide applications. Conventional design methods mainly rely on manual experience and try to calculate in structural optimization. As the scale of the truss increases, the design process is becoming ever more complicated. Some of the problems faced by traditional methods while dealing with large-scale problems include low efficiency and inadequate accuracy. Therefore, based on optimization design theory, the optimization of the mechanical properties of the truss structure has become a research hotspot and an important method for enhancing structural performance and saving materials.

2.2 Basic Principles and Common Algorithms of Optimization Design

The optimization design for truss structures can be defined as the minimum weight or cost by reasonably choosing materials, shape, and structural parameters while design constraints are met, such as bearing capacity and stability, deformation limits. Their basic principle of optimization design takes the principle of structural mechanics into account. The basic process is that the mathematical model first describes the mechanical behavior of the truss structure; then, based on the premise that it meets the constraints, by means of the optimization algorithm, the design variables are adjusted to achieve the best value of the objective function. The commonly used optimization methods can be divided into two kinds: classical optimization algorithms and modern intelligent optimization algorithms. Among the classical optimization methods, main ones include linear programming, nonlinear programming, and dynamic programming. Most of them are based on gradient information and belong to a class of smooth continuous objective functions. In recent decades, along with the development of computer technology, the intelligent optimization algorithms have gradually been applied in the truss structure optimization design, which includes methods such as GA, PSO, and SA. These have good global search capabilities for large-scale optimization problems. The intelligent optimization algorithm can prevent falling into the local optimum and solve the complex nonlinear and multi-constrained optimization problems. During the course of optimization of truss structure design, a proper method of optimization will be able to achieve much higher performances and find the best balance between the structural materials and costs

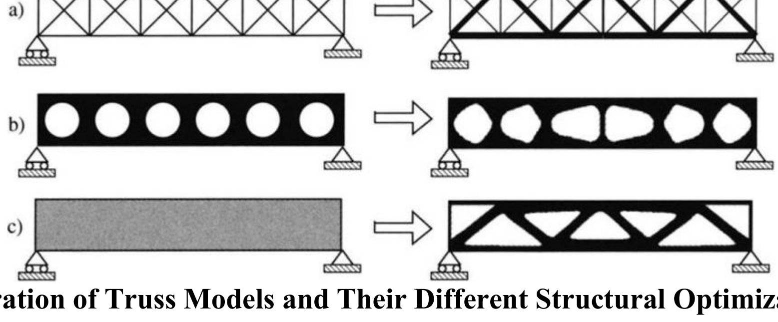

Figure 1. Illustration of Truss Models and Their Different Structural Optimization Categories a) Size, b) Shape and c) Topology (Bendsøe & Sigmund, 2003).

Figure 1 shows three different methods of structural optimization design. For example, as shown in Figure 1a, by increasing the truss diagonal, its stability can be enhanced with better load-carrying capacity without adding too much weight to the structure. Figure 1b presents the design of introducing circular holes in the beam. This design reduces the weight of the structure, while the strength and stiffness of the structure are kept constant by optimizing the material distribution. Figure 1 also further optimizes the material by triangular holes in the beam so that it further improves the mechanical properties. Such optimizations not only provide a better structural economy but also achieve the goal of engineering for sustainable development.

In the optimization design of the truss structure, the usually selected objective is a certain performance index. The typical ones are the weight, the cost, and the rigidity of the structure. For this reason, we have to solve the optimal solution with the aid of an appropriate optimization algorithm within the design space. To explain the basic principles of optimization design, the following example formulae can be used.

First, consider the problem of minimizing the weight of the truss. The objective function is usually expressed as minimizing the weight of the structure. Assume that the total weight W of the truss is the sum of the weights of each component, that is:

$$W = \sum_{i=1}^{n} \rho A_i L_i \tag{1}$$

where ρ is the material density, A_i is the cross-sectional area of the member, L_i is the length of the member, and n is the number of members in the truss.

Then, consider the constraints that need to be satisfied during the optimization process. A common constraint is that the stress of the component does not exceed the tensile strength of the material. For example, the stress σ_i of the i th member should be less than or equal to the tensile strength $\sigma_{\max}$ of the material, that is:

$$\sigma_i = \frac{F_i}{A_i} \le \sigma_{\max} \tag{2}$$

where F_i is the internal force on the member, A_i is the cross-sectional area of the member, and $\sigma_{\max}$ is the tensile strength of the material.

3. Application Analysis of Mechanical Performance Optimization of Truss Structure

3.1 Application of Truss Structure in Engineering Field

Being the essential structural unit in an efficient, economical spatial structure, trusses can present structures widely applied, especially in importance like key bridges, significant building complexes, as well as radio or television towers. In the entire nation, truss appears very often in suspension bridges, railway bridges, as well as cable-stayed ones; the common beam is normally used with strong bearing capacities due to lighter self-weight of its web plate and sometimes because of short construction. For instance, the famous Golden Gate and Charles River Bridges in Boston use truss structure for maintaining high stability and safety in large spans and complex conditions. In construction engineering, the truss structure is used to support large space entities like roofs and floors. For example, the truss structure is often used in the design of a stadium and exhibition center in order to reduce materials and cost while improving space utilization efficiency. Besides, in tower and power transmission tower design, truss structure has already become a common choice in view of its strong ability of resistance to wind and good stability. With the increasing application of truss structure, its mechanical property optimization design has gradually become the key to ensuring structural safety and economy. It is possible to optimize the geometry, component size, and material selection of the truss to greatly improve resource utilization and reduce engineering costs while ensuring structural safety and functional requirements.

3.2 Application and Effects of Different Optimization Methods in Practice

In recent decades, truss structure optimization design has been widely used in engineering practice. Various optimization methods have been continuously adopted to verify their effects. Commonly used methods are the classical methods of mathematical programming, heuristic algorithms, and intelligent optimization algorithms. Their classical versions include linear and nonlinear programming methods, which were widely applied for solving such optimization problems that have clearly presented objective functions and constraints. In practical applications, especially in the optimization results found by these methods, relative accuracy can be achieved, but almost all of them can do little except for small-scale and very simple truss problems due to their limitations. However, in recent years, the genetic algorithm, particle swarm method, and simulated annealing intelligently have been used for ground-breaking optimization of large-span truss structures. These algorithms have strong global search abilities, can effectively avoid falling into local optimum solutions, and are suitable for complex truss design problems with multiple constraints. For example, using genetic algorithms for truss structure optimization, it not only can handle complex geometric shapes but also can perform multi-objective optimization for structural weight, material usage, and cost without increasing the amount of calculation. With methods optimally used in practical engineering applications, the bearing capability and stability of the structure could be massively increased, while material consumption would go down, along with reducing engineering costs, but providing guarantee design safety.

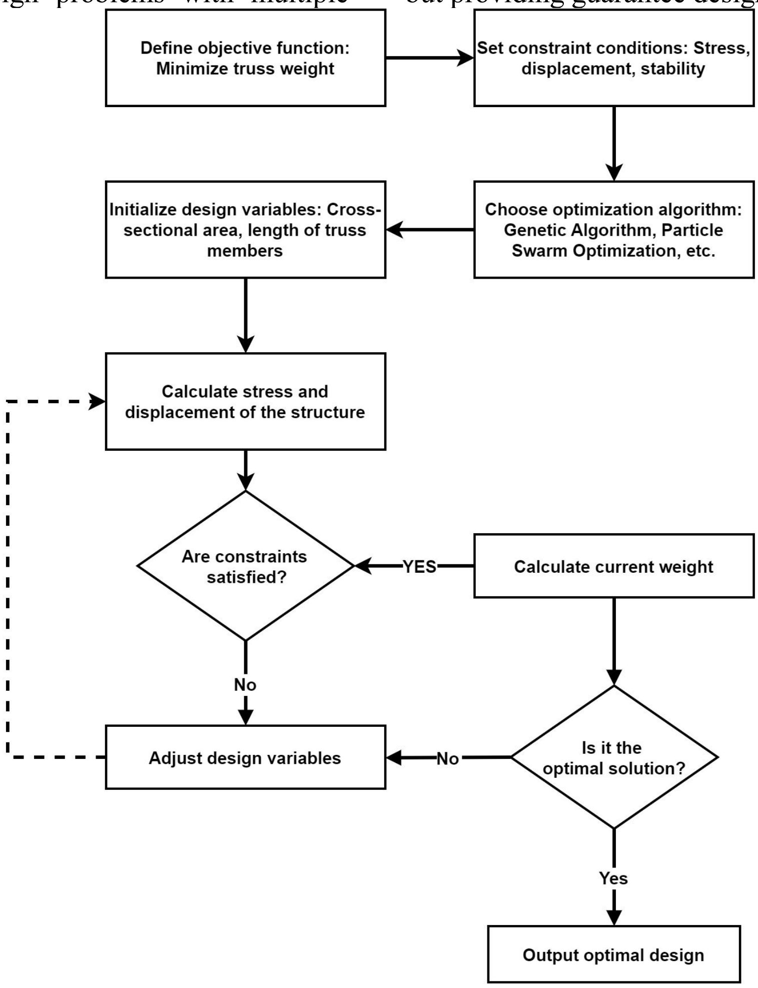

Figure2. Flowchart of Truss Structure Weight Minimization Optimization Process

Figure2 illustrates the iterative process of optimizing the truss structure by minimizing its weight while ensuring that all structural constraints (such as stress, displacement, and stability) are met. The optimization process involves adjusting the design variables, evaluating the structure, and repeating the process until the optimal solution is found.

3.3 Challenges and Experiences in Truss Structure Optimization Design

Although the theoretical and technical development of truss structure optimization design has developed rapidly, there are still many problems in practical applications. First, because of the complexity and diversity of truss structures, the optimization problem may be highly nonlinear, which can easily lead to traditional optimization methods falling into local optimal solutions when solving. Large-scale truss optimization design has gradually applied intelligent optimization algorithms in order to avoid this problem, but the computational cost of these algorithms is very high. Especially for the complex optimization problems with multi-constraints and multi-objectives, large amounts of computing resources are often needed. In addition, in the truss structure of real engineering, there are always various external factors, such as environmental conditions, changes in material properties, construction errors, etc., which make the optimization design more difficult. Another big problem is the optimization of new material and complex truss structure. The current theory and methods of optimization, in the balance between the mechanical properties and costs, are still hard to satisfy these new requirements. However, the experiences accumulated in practice show that the use of reasonable optimization models and algorithms in conjunction with efficient computing tools and accurate experimental data can effectively overcome these difficulties. The optimization design can not only improve the performance of truss structures but also reduce construction costs and improve resource utilization efficiency. Therefore, with the development of related technologies, the application prospect of truss structure optimization design is still broad, especially in engineering practice; the gradual realization of the connection between theory and actual needs will surely promote the more efficient and accurate development of truss structure design.

4. Future Development Direction and Challenges

4.1 Application of New Materials and Intelligent Optimization Methods

With the continuous development of engineering technology, the application of new materials has become an important direction for the optimization design of truss structures. High-performance materials represented by carbon fiber composite materials, ultra-high strength steel, and intelligent materials have high strength, toughness, and corrosion resistance, which can significantly improve the bearing capacity and durability of truss structures. At the same time, with the development of material science, structural lightweight and energy saving and emission reduction become key requirements for design. Meanwhile, intelligent optimization methods provide more efficient solutions for truss structure optimization. Genetic algorithms, particle swarm optimization algorithms, and ant colony algorithms are some of the intelligent methods that can realize a global search in complex design space by the simulation of the evolution process of nature, avoiding local optimal problems that might appear in using traditional optimization. These new material combinations and intelligent optimization methods will not only improve the performance of truss structures but can also effectively reduce costs and material consumption, furthering the development of structural design to a much higher intelligent and environmentally protective level.

4.2 Progress in Interdisciplinary Technology Integration and Computational Methods

The complication in the truss structure optimization design has been in continuous development both in disciplines and computational methods. Structurally, the cross-integration technology includes integration of the structure mechanics, material science, computer science, artificial intelligence, and other fields, which provides novel technical support for the optimization design of the truss. For example, on the basis of integrating such technologies as finite element analysis, multi-objective optimization design can provide more accurate solution results that meet multiple design indices. Meanwhile, cloud computing, big data technology has enabled great enhancement in truss-structure analysis and optimization to be made. The enhancement in computing power can make the optimum solution for large-scale, multiconstrained, and multiobjective truss optimization within a relatively short time and continue to enhance efficiency, preciseness, and automatization of truss design effectively. It can be seen that, with the further integration of interdisciplinary technologies, in-depth development, and intelligent manufacturing technology, the future optimal design of the truss structure will be more reasonable and comprehensive, and the application scope will be larger. More complex engineering requirements can be tackled.

4.3 Future Development Prospects of Truss Structure Optimization Design

The prospect for future development in the truss structure optimization design is very encouraging. Along with betterment in computing technology and material science, the design of the truss structure will enter a new era characterized by high efficiency and intelligence. Future truss design will no longer focus only on the mechanical properties of the structure itself but also on more selections of materials, cost optimization, and environmental friendliness. Adopting advanced intelligent algorithms and big data analysis, it will be able to customize truss structures in a wider range of application scenarios to meet different engineering needs. The trend that this optimization design in truss structures is going to be facing will be toward sustainability for structural safety, energy economy, and waste reduction. Also, considering the impact on the environment in its applications and promoting the use and implementation of new building materials to push through Green Building concepts. In a word, driven by future technologies, the optimization design of truss structures will develop toward more efficiency, precision, environmental friendliness, and intelligence, providing more competitive solutions for modern engineering construction.

5. Conclusion

In this light, this paper has made a systematic analysis on the research progress and application of truss structure mechanical property optimization design. Together with the increase in modern engineering requirements' complexity, truss structures, because of their efficient and economic load-carrying form, have been widely used in modern bridges, buildings, and towers. The core of the truss structure optimization design is to maximize the mechanical properties and economic benefits of the structure by reasonably selecting design parameters such as materials, shapes, and sizes. Although the traditional truss design method has achieved good results in small-scale and simple structures, it still faces challenges such as low efficiency and insufficient precision when dealing with complex and large-scale truss structures. Optimization theory and methods, especially applications of intelligent optimization algorithms along with new materials, have more efficaciously and precisely solved the single truss structure optimization in hand.

In the future, truss structure optimization design will continually develop towards intelligence and greening. With new material application, truss structure performances can be highly improved. Moreover, complex constraints and multi-objective optimization problems can be treated more effectively by some intelligent optimization methods. In addition, interdisciplinary technologies such as integrating computational power could make truss structure optimum design much more automatic and effective.

Although the optimization design of the truss structure still faces some technical and computational difficulties nowadays, with the continuous development of related technologies, the optimization design of truss structures will play an increasingly important role in engineering practice and promote engineering construction in a more refined, sustainable, and intelligent direction.

References

[1] Cai, Qi & Feng, Ruoqiang & Zhang, Zhijie. (2022). Topology optimization of truss structure considering nodal stability and local buckling stability. Structures. 40. 64-73. 10.1016/j.istruc.2022.04.008.

[2] Tejani, Ghanshyam & Thummar, Dhaval. (2014). Truss Topology Optimization Using Modified Genetic Algorithm. 10.13140/RG.2.1.1481.3929.

[3] Liu, Jikai & Yu, Huangchao & To, Albert. (2018). Porous structure design through Blinn transformation-based level set method. Structural and Multidisciplinary Optimization. 57. 1-16. 10.1007/s00158-017-1786-1.

[4] Wang, Jianghong & Cui, Changyu & Jiang, Baoshi. (2023). An Integrated Shape Optimization Method for Hybrid Structure Consisting of Branch and Free-Form Surface. Applied Sciences. 14. 334. 10.3390/app14010334.

[5] Ondocko, Stefan & Svetlik, Jozef & Jánoš, Rudolf & Semjon, Ján & Dovica, Miroslav. (2024). Calculation of Trusses System in MATLAB - Multibody. 10.20944/preprints202410.0003.v1.

[6] Xu, Tao & Huang, X. & Lin, Xiaoshan & Xie, Yi. (2024). Topology optimization of continuum structures for buckling resistance using a floating projection method. Computer Methods in Applied Mechanics and Engineering. 429. 117204. 10.1016/j.cma.2024.117204.

[7] Ribeiro, Tiago & Bernardo, Luís & Carrazedo, Ricardo & De Domenico, Dario. (2024). Topology optimisation of steel connections under compression assisted by

physical and geometrical nonlinear finite element analysis and its application to an industrial case study. Structural and Multidisciplinary Optimization. 67. 10.1007/s00158-024-03799-7.

[8] Zhao, Zhongwei & Kang, Ziwen & Zhang, Tongrui & Yan, Renzhang & Zhao, Bingzhen & Wang, Shichao. (2024). Construction optimization of spatial arch bridges based on inverse hanging and RGA method. Structures. 64. 10.1016/j.istruc.2024.106636.

[9] Kostic, Nenad & Petrovic, Nenad & Marjanovic, Vesna & Nikolić, Ružica & Szmidla, Janusz & Marjanovic, Nenad & Ulewicz, Robert. (2024). Effects of Limiting the Number of Different Cross-Sections Used in Statically Loaded Truss Sizing and Shape Optimization. Materials. 17. 1390. 10.3390/ma17061390.

[10] Morillas, Abraham & Meneses, Jesus & Bustos, Alejandro & Castejón, Cristina. (2024). Sensitivity Analysis and Filtering of Machinable Parts Using Density-Based Topology Optimization. Applied Sciences. 14. 6260. 10.3390/app14146260.