Research On the Optimization Methods of Truss Structure Based on Three Basic Truss Mechanical Analyses

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Abstract. In this research, the historical development and characteristics of truss structure are briefly summarized, and the development track of truss calculation theory is introduced. In view of the triangle, square and folded trusses, the stress analysis is carried out and its distribution characteristics are obtained, then drew the conclusion of the practical engineering scene, finally got the result of the prospect of the truss structure and its optimization.

Keywords: Optimization of truss structure, triangular/rectangular/poly line truss, internal force analysis.

1. Introduction

Since the beam bears the load, mainly produces the internal bending force, the stress distribution on the section is not uniform, so the material cannot be fully used. The truss is a structural system composed of bars. When the load only acts on the nodes, the internal force of each bar is mainly axial force, and the stress on the section is evenly distributed, which can give full play to the role of materials. Therefore, the truss is a common form of a large-span structure [1]. The introduction of a truss optimizes the whole structure to make its internal force distribution more reasonable.

2. Development of Truss Calculation Theory

Truss is an important symbol of structure optimization. For truss calculation theory, it experienced the process-from Static analysis of basic mechanics (Structural mechanics, Mechanics of materials, Elastic mechanics) to Finite element modeling analysis, then developed to the method of Bionic intelligent optimization algorithm.

2.1. Static Analysis of Basic Mechanics

In the evolution of truss calculation methods, the theory of Static analysis of basic mechanics only played a tiny part of the whole process, since its low calculation efficiency, but it laid the solid foundation for the development of truss calculation. In structural mechanics, internal force calculation is mainly based on structural analysis. For statically determinate plane truss, the section method and node method are used to calculate the internal force. In special cases (statically indeterminate structure, considering the elastic deformation of the whole structure...) Force method and displacement method will be used for calculation [1]. In the later development process, considering the emergence of dynamic load, energy principle [2] and structural matrix analysis [3] also appeared on the stage, paving the way for algorithm optimization theory in recent years. This method is easy to calculate for large scale structures and can be used for engineering prediction. However, it is not applicable to design optimization of complex structures.

2.2. Finite Element Modeling Analysis

2.2.1 Basic Introduction to Finite Element Theory

The finite element method originated from the study of elastic and structural analysis in civil engineering and aeronautical engineering. Its development can be traced back to the work of Alexander Hrennikoff (1941) and Richard Courant (1942). Finite element method (FEM) was first proposed by COURANT R in 1943 and developed by aeronautical structural engineers in 1950s. It is a kind of numerical calculation. This method was then widely applied to other engineering fields in the 1960s. Due to its versatility and effectiveness, the finite element method is highly valued by various engineering industries, and has become the most widely used numerical calculation method in the engineering industry.

Because there are too many uncertain factors involved in the actual engineering operation process, it is generally impossible to obtain the exact solution, so we can only obtain the numerical solution by numerical calculation to approximate the exact solution [4].

At present, there are two kinds of exact solutions, one is finite difference method, the other is finite element method. Finite element method (FEM) is the most widely used numerical method at present. At the same time, finite element method is also significantly used in other engineering fields such as architecture, aerospace, nuclear engineering [5, 6].

2.2.2 Practical Application of Finite Element Method

(1) Establishing finite element model: Taking ANSYS as an example, the space truss model is established and the element attributes are given. During the modeling process, the upper and lower strings, vertical bars, belly bars and beams were simulated as required.

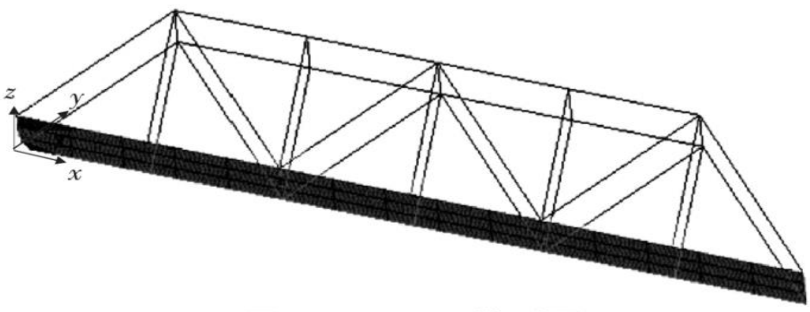

Figure1. ANSYS Model

(2) Analyzing the load properties according to the model: static and dynamic forces are generally discussed separately in the analysis process. In static analysis, the theoretical results are generally compared with the known properties of the truss, and the numerical solutions are checked with the design values to test the reliability of the model.[7] In dynamic analysis, the seismic response analysis method [8] is used to discuss the safety and failure mechanism of the structure under earthquake.

2.3. Bionic Intelligent Optimization Algorithm.

In recent years, due to the observation and analysis of natural organisms, and with the aid of bionics and humanities theories, many bionic optimization algorithms have been proposed which can embody good functional level. Because these algorithms can realize self-repair ability and self-learning to a certain extent when dealing with complex actual situations, their solving ability will not be affected even in the face of special situations. These capabilities enable the bionic intelligent algorithm to occupy a dominant position in the optimization of truss structures. Common bionic intelligence algorithms include ant colony optimization algorithm (ACO), particle swarm optimization algorithm (PSO) and whale optimization algorithm (WAO) proposed two years ago, which has been significantly improved in convergence accuracy and optimal solution.

Particle swarm optimization algorithm (PSO): Particle swarm optimization (PSO) is a kind of evolutionary computation, which was proposed by Dr. Eberhart and Dr. Kennedy in 1995.[9] The algorithm is a simplified model based on swarm intelligence, which is inspired by the regularity of bird cluster activity. On the basis of observing the activity behavior of animal cluster, particle swarm optimization (PSO) makes use of the information sharing of individuals in the group to make the movement of the whole group evolve from disorder to order in the problem-solving space, so as to obtain the optimal solution. According to tang Hesheng's theoretical research,[10] PSO algorithm can successfully optimize the shape design of truss structure, with fast convergence speed, good stability and effectiveness. This is no small breakthrough in truss structure optimization.

Whale optimization algorithm (WOA) and its improvement: Whale Optimization Algorithm (WOA) is an emerging population intelligent Optimization Algorithm. It was first proposed by Mirjalili et al from Griffith University in Australia in 2016. Whale optimization algorithm is a meta-heuristic algorithm based on swarm intelligence. Consistent with the general nature-inspired swarm intelligence algorithm, the whale optimization algorithm searches for the optimal solution by simulating the hunting behavior of humpback whales. The whale optimization algorithm is mainly divided into three steps: search for prey, bubble attack, and search for prey. Finally, the coordinate position of prey is obtained through calculation, that is, numerical calculation value.[11] Due to the simple algorithm principle, whale optimization algorithm has a large global search range and can output the optimal solution at the end of the iteration cycle. At the same time, the simple algorithm program, easy to program operation, reduce the requirements for the computer, easy to use the algorithm to test the feasibility of the function.[12] However, the bionic intelligent algorithm has remarkable characteristics, which is not conducive to the overall application.

3. Analysis of Mechanical Properties of Truss

3.1. Basic Truss Type

In engineering, a truss is a structure that "consists of two-force members only, where the members are organized so that the assemblage as a whole behaves as a single object".[13] This paper uses three typical types of trusses-triangular, rectangular, and folding to draw the conclusion.

3.1.1 Triangular Truss

Triangular truss also known as Warren truss In structural engineering, a Warren truss or equilateral truss is a type of truss employing a weight-saving design based upon equilateral triangles. It is named after the British engineer James Warren, who patented it in 1846. The Warren truss consists of longitudinal members joined only by angled cross-members, forming alternately inverted Equilateral triangle-shaped spaces along its length. This gives a pure truss: each individual strut, beam, or tie is only subject to tension or compression forces, there are no bending or torsional forces on them.

3.1.2 Rectangular Truss

Rectangular truss is the particular form of Pratt truss. The Pratt truss was patented in 1844 by two Boston railway engineers, Caleb Pratt and his son Thomas Willis Pratt.[14] The design uses vertical members for compression and diagonal members to respond to tension. The Pratt truss design remained popular as bridge designers switched from wood to iron, and from iron to steel [15].

3.1.3 Folding Truss

Folded trusses are geometric variations of triangular and square trusses and play a special role in structural optimization. This can be clearly reflected in the conclusion of mechanical analysis in the following chapters.

3.2. Establishment Of Truss Mechanical Model

In order to draw the result easily, the paper puts two-unit load acting at the second joint of lower chord each from the right and left end, making it a symmetrical structure. Therefore, we only need to find the internal forces of a half, and then the other half will be gotten. According to the standard, the paper designs each bar with a length of 2500 mm (2.5 m) to form a bridge of 25 m. The internal forces are calculated through the bars for three different types of trusses (triangular, rectangular, and poly line truss). Finally, the maximum load of bars that would suffer from each type of truss will be compared. The bigger the force is, the faster it will break, which means it is not so proper to choose that type of truss as the structure of the bridge. Since the paper designs, the bridge with the same material so the same strength.

3.3. Solution Of Truss Mechanical Model

Since the chosen type of trusses are relatively basic, so this chapter would choose the method of structural mechanics to do internal force analysis, to facilitate conclusions.

(1) Triangular Truss [16]

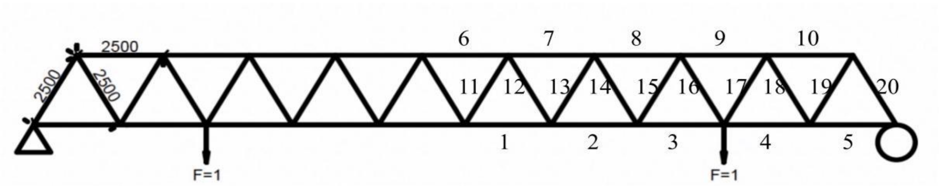

Figure 2. Triangular truss planar model

In the process of calculation, the combination of the method of joints and sections will be used. Firstly, separate the structure into two parts with one cutting, then consider the small part as the start of the calculation. Here we use three equilibrium equations to figure out the loads acting on the bars, which are$\sum F_x = 0$ (horizontal equilibrium) $\sum F_y = 0$ (vertical equilibrium) and $\sum M = 0$(moment equilibrium), therefore the structure will be translational equilibrium and also rotational equilibrium. When we need to use the method of section to find out any three forces in the section, we can take the pivot at the joint which two of them would pass through, so the rest of the force will be easily figured out, using moment equilibrium simplifying the calculation. The form followed would show the internal force analysis of this triangular truss i designed.

Table1. Internal forces of triangular truss

Loads act on Upper chord	6: 2.61	7: 2.56	8: -2.43	9: -2.31	10: -1.2
Loads act on Lower chord	1: -2.56	2: -2.43	3: 2.31	4: 1.2	5: 0.6
Loads act on Oblique abdominal rod	11: 1.2	12: 1.2	13: -1.2	14: 1.2	15: -1.2
	16: 0	17: 1.2	18: -1.2	19: 1.2	20: -1.2

Under the data provided above, the calculation comes up with the maximum internal force with 2.61. what's more, data also shows the trend of the loads act on different type bar in the truss-The internal force of truss is mainly axial force, the upper chord is pressed and the lower chord is pulled. The stress increases from both sides to the midspan which means the maximum stress occurs at the midspan. In addition to the different tensile and pressure properties of the oblique belly bar, 16 is zero bar, and the rest stresses are all the same in magnitude. Besides the calculation. Today's most widely used triangular truss, also known as the Warren truss was patented in 1840, around the same time as Hown and others, but did not catch on in the 19th century. Warren trusses are the "minimalist" members of the truss family, consisting of the simplest equilateral triangles superimposed along the span to form a truss beam. When the span increases, the vertical bar can be used to divide the equilateral triangle into two right triangles to reduce the joint spacing and improve the support stiffness of the deck system [17].

(2) Rectangular Truss

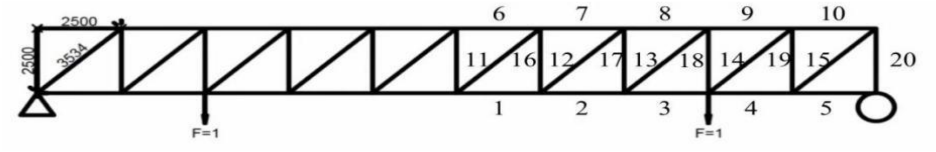

Figure 3. Rectangular truss planar model

Table2. Internal forces of rectangular truss

Load act on Upper chord	6: 0	7: -2	8: 0	9: -2	10: -1
Load act on Lower chord	1: -2	2: 0	3: -2	4: 1	5: 2
Load act on Oblique abdominal rod	11: 2.82	12: 2.82	13: 2.82	14: 1.41	15: -1.41
Load act on Vertical web member	16: 2	17: 2	18: 2	19: -1	20: -1

We can easily calculate each bar load for this type since each part is totally the same and each angle is 45 degrees. Here the paper comes up with the maximum load $2\sqrt{2}$ (2.82). During the calculation, the paper found that the oblique ventral bar is under tension and compression, and the force direction of the vertical ventral bar is opposite to that of the oblique ventral bar. Besides, although there is no linear variation relation for the member, it can still be observed that there are quite a few zero bars with a calculated value of 0 at the position of the upper and lower chord.

(3) Poly Line Truss

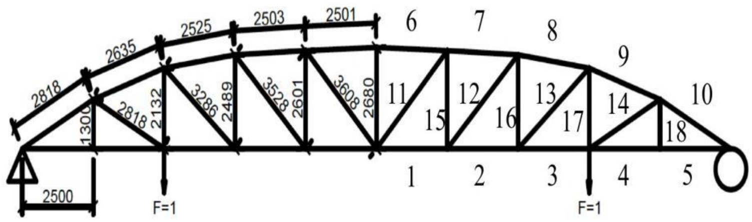

Figure 4. Poly line truss planar model

Table3. Internal forces of folding truss

Loads act on Upper chord	6: -1.87	7: 1.91	8: -2.05	9: -2.17	10: -2.47
Loads act on Lower chord	1: 3.34	2: 3.46	3: 2.34	4: 1.91	5: 1.93
Loads act on Oblique abdominal rod	11: 2.13	12: 1.72	13: 1.23	14: 0.48	
Loads act on Vertical web member	15: 1.17	16: 0.95	17: 0.78	18: 0	

This type of truss is the most complicated structure among them since we need to calculate the actual degree between each bar at first, so we need to use the ratio of two lengths to represent the value of cosine and sine. After the repetitive calculation, the essay gets the maximum value of 3.46(correct to two decimal places). Compared with the triangular truss, the internal force distribution of the folded truss shows an opposite trend. Except for the belly bars, the internal force of the upper and lower chord bars decreases from both sides to the middle span, and the maximum stress appears on both sides.

So now, the paper compares their value and draws the conclusion that the maximum value of polyline truss is much bigger. Therefore, the stability of them is triangular truss>rectangular truss>poly line truss.

4. Truss Form Selection

In the analysis of mechanical properties in chapter 3, we can draw a conclusion. According to the above-mentioned conditions of applying concentrated load, the stress distribution of triangular truss shows a trend of decreasing from mid-span to both sides. Therefore, the triangular truss is suitable for the engineering site where the load of two spans is the largest and decreases in the middle of the span. As for rectangular truss (Pratt truss), In fact, due to the configuration of the members means that longer diagonal members are only in tension for gravity load effects. This allows these members to be used more efficiently, as slenderness effects related to buckling under compression loads (which are compounded by the length of the member) will typically not control the design. Therefore, for given planar truss with a fixed depth, the Pratt configuration is usually the most efficient under static, vertical loading. For the folded truss, the maximum stress appears in the middle of the span, and the stress distribution increases from the middle of the span to both sides, so it is suitable for the scene where most of the external load is distributed in the middle of the span. This stress distribution is consistent with the current stress conditions of beam Bridges, which is also the reason why the folded truss is widely used in beam truss Bridges.

5. Examples of Truss Engineering

Due to the structural characteristics of triangle truss and square truss, they are generally combined and mainly used in roof trusses to resist natural loads such as snow load and wind load...... Here i would introduce two applications, a particular roof and a bridge respectively. Among the large-span structures, the earliest extant record is the Equestrian stadium in Moscow, designed and built by Betacuru in 1818. The length and width of the building is 160x50m. The span of the long-span wooden triangular trusses is 50m along the short side and 5.8m apart. With a span much longer than conventional buildings of the same period, the triangular trusses are embedded with three trapezoidal trusses to resist the huge and uneven snow load.[18]

The Sellwood Bridge is a two-lane structure over the Willamette River at the south edge of Portland. It now carries about 30,000 vehicles per day, the heaviest-traveled two-lane bridge in Oregon. The approach spans are reinforced concrete, and the main spans are four continuous subdivided Warren-type deck trusses with span lengths of 246, 300, 300, and 246 ft, respectively.[19] For folding truss.[20] The Waibaidu Bridge in Shanghai, China's first all-steel riveted bridge, opened to traffic on January 20, 1908. The bridge is a simply-supported steel truss with two holes spanning 52.12 meters each. Trolley tracks are laid on the bridge deck.

6. Conclusion and Prospect

6.1. Conclusion:

Truss calculation theory has experienced a process from basic mechanics, to numerical analysis of algorithm, to intelligent algorithm, self-learning to quickly obtain the optimal solution, and its development process is still progressing.

For this determinate 25m truss bridge, when we add external load acting on a single joint rather than uniformly distributed on the beam, the paper gets the result: Stability truss>rectangular truss>poly line truss.

The above calculation results show that, under concentrated load, if the external load acts on the midspan is the largest, the internal force distribution of the triangular truss is more reasonable.Therefore, triangular trusses should be selected. In the face of continuous load and maximum external stress at the two supports, the folded truss should be selected.

6.2. Prospect

By observing the historical process of truss structure, its inherent form is constantly changing, and the algorithm theory is also improving. Under the research of this paper, although there are many optimization methods, it is still a problem to be solved which optimization scheme to choose according to the truss. In the future, such problems can be solved through big data statistics and other methods.

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