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Design Suggestions of Plane Truss Structure Based on Mechanical Performance Optimization

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Abstract. This article systematically studies the geometric parameter optimization design method for planar truss structures, focusing on three typical truss forms: parallel chords, triangular shapes, and parabolic shapes. Through parametric modeling and mechanical analysis, the influence patterns of key parameters such as the height-to-span ratio, web member angle, and upright tube arrangement on structural stiffness, internal force distribution, and economy have been clarified. Research shows:optimization of macro-form (such as adopting triangular or parabolic trusses) can bring about a stiffness improvement of over 20%, with significantly higher benefits than local parameter adjustments (8%-15%);the optimal combination of parameters is a high-span ratio of 1/9, a web member angle of 45°-55°, and a triangular/parabolic truss. Practical verification shows thatCompared to traditional designs, this method can reduce material usage by 12%-18% while simultaneously enhancing stiffness by over 25%. It achieves a synergistic optimization of mechanical performance and economy, providing a systematic solution for the scientific selection and refined design of truss structures.

Keywords: Plane Truss, Static Load, Mechanical Performance Optimization, Mid Span Deflection

1. Introduction

Plane truss is a classical plane structure system composed of straight members, it is widely used and plays an important role in bridges, roofs, towers and various long-span engineering structures [1]. The diversity of its geometric forms, including parallel strings, triangles and parabolas, directly affects the mechanical properties and load transfer efficiency of the structure. The truss structure has the outstanding advantages of light weight, high efficiency and clear stress path. It is of great significance to achieve the goals of economy, lightweight materials and excellent performance pursued by contemporary engineering [2]. However, The current design practice still generally relies on empirical formulas and conventional values, lack of systematic mechanical theory support and quantitative optimization analysis for the selection of key design parameters such as height span ratio, web member inclination and vertical member arrangement. As a result, the potential of the structure has not been brought into full play, and it is difficult to fully adapt to the increasingly complex and refined requirements of modern engineering.

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Therefore, combining rigorous mechanical analysis principles with advanced structural optimization theory, deeply and systematically study the internal laws between truss geometric parameters and its overall mechanics [3], It not only helps to make up for the shortcomings of the existing design methods. It is also the key to promote the evolution of structural engineering design to a more scientific, accurate and efficient direction.

In this paper, plane truss is the main research object, covering different geometric forms, web member angle and other variables. Through parametric modeling and analysis of the system, the purpose is to clarify the comprehensive effects of variables such as span, load distribution, web member angle, height span ratio and vertical member setting on the internal force distribution, deformation characteristics, bearing capacity and material economy of the structure. Then a set of truss type selection and optimization design method system based on mechanical properties and quantifiable evaluation is established.

2. Data calculation

2.1. Comparison and calculation of truss structures with three different geometric forms

Table 1. comparison of deflection, material consumption and construction complexity of three different geometric truss forms

Truss form	Mid-span deflection (relative value)	Material Dosage (Relative Value)	Construction complexity
Parallel strings	9. 58	0. 85	low
Triangle	7. 49	1. 00	middle
Parabolic	4. 67	0. 92	middle

The selection of truss structure is a process of comprehensive consideration of mechanical properties, material economy and construction feasibility [4]. Table 1 shows the deflection, material consumption and construction complexity of three different geometric truss forms. As classic forms, parallel chord, triangle and parabola truss have distinct technical and economic contrasts. Parallel chord truss is good at its standardized structure and low construction complexity. All members are parallel and equal in length, and the nodes are unified [5]. The manufacturing and installation cost is the lowest. However, its mechanical properties are obviously short, the relative deflection in the middle of the span is as high as 9. 58, and the stiffness is insufficient, this is because the internal force distribution of the chord does not match the bending moment diagram, showing the characteristics of "large in the middle and small at both ends". The material properties are not fully utilized, so it is only applicable to small span (≤ 20m) scenes with low stiffness requirements. Triangular truss shows excellent comprehensive balance, Its shape is in good agreement with the bending moment diagram [6]. The mid span deflection (7. 49) is significantly better than that of the parallel chord, Large height at both ends is conducive to controlling the angle. Although the material consumption is the highest as the benchmark value (1. 00) and the construction complexity is medium, it has outstanding cost performance in the application of medium span (20-50m) and has become the mainstream choice in engineering practice. Parabolic truss represents the theoretically optimal form of mechanics, Its geometric shape accurately fits the bending moment diagram[7]. Make the chord axial force distribution extremely uniform (the range is only 0.28), The optimization of internal force transmission path is realized. This results in excellent structural stiffness (minimum deflection, 4.67) and ultra-high material efficiency (steel consumption 0.92, lower than triangular truss). However, the length and joint angle of each member are different, the complexity of design,

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manufacture and installation is the highest, and the construction cost is soaring. Therefore, it is usually used for large-span (>50m) important structures pursuing ultimate performance.

From the calculated data, the core laws can be extracted:the stiffness performance directly depends on the fit of the shape to the bending moment diagram [8], Parabola shape is the best, triangle is the second, and parallel chord is the weakest;And the material economy presents a deep problem -- not the simplest form and the most economical material. Parabolic shape achieves greater stiffness with less materials, It is revealed that the essence of structural efficiency is to fully stimulate the material properties by optimizing the geometric shape. The construction complexity increases with the decrease of shape regularity, It directly reflects the inherent contradiction between mechanical efficiency and construction convenience. The comprehensive selection shall follow the span dominant principle:Parallel chord can be selected for small-span heavy economic construction, triangle should be used for balance and reliability of medium-span, and parabolic shape can be considered for performance efficiency of large-span. Different forms of mechanical logic need to be systematically weighed in decision-making.

2.2. Effect of web member angle on structural performance

Table 2. Comparison of structural performance at different abdominal rod angles

Abdominal rod angle	Maximum mid-span deflection (relative value)	Risk of buckling under compression
18.4°	15.81	High (excessive compression on the diagonal brace)
45°	4. 24	low
54°	3. 91	Extremely low
60°	4. 12	low

In the design of truss structure, the selection of web member angle is the key parameter to determine the overall performance, which has a profound impact on the stiffness, internal force distribution and stability of the structure [9]. Table 2 shows the structural performance comparison under different web member angles. The calculated data clearly reveals the performance law under angle change:when the angle of web member is 18. 4 °, the relative deflection at midspan is as high as 15. 81, and the inclined member bears huge axial pressure, so the risk of instability is significant. When the angle increases to 45 °, the deflection drops sharply to 4. 24, and the stability is greatly improved, showing a qualitative leap in performance;At 54 °, the deflection is the smallest (3. 91), the axial force distribution is the most balanced, and the risk of instability is very low. While the angle continues to increase to 60°, the deflection slightly rises to 4.12, indicating that there is a limit to the performance improvement.

This trend reveals the core law of Engineering Mechanics:the performance optimization of the structure is not monotonous and linear. In the range of 18. 4° to 45°, the effect of increasing the angle on stiffness is very significant, showing the characteristics of increasing marginal benefit;However, when the angle exceeds 45°, especially near 54°, the rate of stiffness improvement slows down significantly, showing a diminishing marginal benefit, which means that simply increasing the angle is no longer economic. The reason why 54 ° is the best of the theory is that it realizes the geometric optimization of the internal force transmission path—the angle between the web member and the chord member enables the axial force to be most evenly distributed in the member network. Thus, the local stress concentration and the overall deformation are minimized under the premise of similar material consumption [10].

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From the perspective of engineering practice, the following hierarchical selection views can be obtained:First of all, the small angle design must be avoided. Its insufficient stiffness and high risk of instability constitute a serious potential safety hazard. It should not be used unless it is limited by extreme structure and supplemented by special reinforcement. Secondly, for most conventional projects, 45° is an excellent practical choice, which has achieved the best balance between performance, construction convenience and economy, simple node structure, and low difficulty in calculation and setting out. Moreover, in important long-span structures with extreme requirements for stiffness, stability or lightweight, it is recommended to use an optimization interval of 52° -56 °, which can obtain performance benefits close to the theoretical limit at a small cost.

The final design decision should be made under the comprehensive constraints of span, load, material, construction accuracy and building space [11]. Through the fine regulation of the "detail" of the web member angle, the safety, efficiency and economy of the structure can be promoted at the least cost [1].

2.3. Effect of height span ratio on structural performance

Table 3. Comparison of structural performance under different slenderness ratios

High aspect ratio	Axial Force Extremum (Relative Value)	Maximum mid-span deflection (relative value)	Material Usage Trends
1/6(Big)	0. 32	9. 66	More
1/9(middle)	0. 45	19. 95	Medium
1/12(Small)	0. 61	34. 38	Less

In truss structure design, the determination of height span ratio is a core decision, which accurately adjusts the balance of structural stiffness, material economy and building space. Table 3 shows when the height span ratio increases from 1/12 to 1/9 and then increases to 1/6, the nonlinear deflection at midspan decreases sharply (34.38 → 19.95 → 9.66), and the stiffness of 1/6 scheme is more than 2.5 times higher than that of 1/12 scheme;The range of axial force was optimized from 0. 61 to 0.32 synchronously, which showed that the internal force distribution was significantly improved. This change stems from the mechanical principle that the bending stiffness is proportional to the square of the effective height—increasing the height can restrain the deformation by geometric multiple, and improve the material utilization efficiency by extending the internal force arm [12]. However, the stiffness gain is accompanied by a clear cost:With the increase of the height span ratio, the material consumption increases by about 20%, of which 1/9 is at the "marginal benefit inflection point" of stiffness gain and material cost.

The three schemes correspond to different engineering logics, the 1/6 scheme is the preferred choice for performance. It exchanges about 20% of the material increment for more than 2. 5 times of the stiffness improvement. It is suitable for large-span and heavy-duty key structures, but the material consumption is the largest and the net height is compressed. The 1/9 scheme reflects the optimal cost performance balance, just before the critical point of sharp rise in cost, meets the needs of conventional projects, and is the benchmark choice for the optimal life cycle cost. The 1/12 scheme is a space economy strategy, with the least material but significantly reduced stiffness. It is only applicable to secondary structures or space constrained scenes, and needs to be strictly checked.

To sum up, the decision-making of height span ratio is a comprehensive consideration that integrates the principles of mechanics, economic analysis and spatial planning. 1/9 is a reliable starting point based on science. Tilt to 1/6 is to pay a premium for performance; Moving closer to

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1/12 is the consideration of economy and space demand, which is the precise coordination of structural safety, economy and architectural intent.

2.4. Effect of vertical pole on the performance of truss structure

Table 4. Comparison of structural performance with and without uprights

Upright position	Mid-span deflection (relative value)	Stiffness increase	Increase in material usage	Applicable Scenarios
There is a pole	3.91	28.6%	9.2%	Long Span / Heavy Load
Without upright pole	5.48	-	-	Short to medium span / Light load

In the truss design, the setting of intermediate vertical rod can significantly improve the stiffness. As shown in Table 4, the mid span deflection of the scheme with vertical pole (3.91) is 28. 6% lower than that of the scheme without vertical pole (5.48), and the stiffness is significantly improved, but the material consumption needs to be increased by 9. 2%. This difference is due to the change of the internal force transmission path of the vertical rod, which converts the chord bending moment into axial force, and effectively inhibits the deformation by adding internal constraints.

From the perspective of engineering application, the scheme with vertical pole can exchange 9. 2% material increment for 28. 6% stiffness improvement, which has significant efficiency, and is especially suitable for structures with large span, heavy load or strict requirements for deformation control. The scheme without vertical pole is more economical and simple in structure, which is suitable for occasions with small and medium span, light load and low deformation requirements.

Comprehensive evaluation shall be made when making decisions:If the stiffness is a controlling factor (such as long-span bridges and gymnasiums), the pole setting scheme should be given priority;If economy and construction convenience are the dominant factors (such as light plant and temporary structure), the pole less scheme is more appropriate [13]. In essence, this is a precise consideration of structural efficiency and construction cost.

3. Result

Table 5. Results analysis

Engineering scenario	Recommended parameter combination	Data Support Highlights
Short span (≤20m) +light load	Parallel strings + Without upright pole + Abdominal rod 45°+ High span ratio 1/12	Material usage reduced by 8%-10%,Deflection ≤ 10mm
Medium span (20-50m)+ Conventional Load	Triangle + Has a pole + Abdominal rod 50°+ High span ratio 1/9	Balance between stiffness and economy
Long span (≥50m)+ Heavy load	Parabolic + There is a pole+ Abdominal rod 54°+ High span ratio 1/6~1/9	Deflection ≤ 5mm,Optimal uniformity of axial force (
Dynamic / Impact load	Triangle / parabolic+ Reinforce the pole+ Abdominal rod 55°+ High span ratio 1/6	Corner ≤ 3 rad,The risk of instability is extremely low

In the systematic optimization of truss structure, the choice of macro form is more decisive than the adjustment of micro parameters. As shown in Table 5, optimizing the parallel chord truss to a better form such as triangle or parabola shape can bring more than 20% of the stiffness increase. However, the gain is usually limited between 8% and 15% only by adjusting local parameters such as web member angle or height span ratio.

Based on this, a verified comprehensive optimal parameter combination is to adopt the triangular or parabolic truss, with a height span ratio of about 1/9, and the web member angle is set in the range of 45° -55°. This combination realizes multi parameter synergy:The stress of triangular truss is

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clear and balanced, and the mechanical efficiency of parabolic truss is the best; The height span ratio of 1/9 is just at the inflection point of marginal benefit between stiffness gain and material cost; The web member angle of 45°-55° achieves the best balance among stiffness, stability and node structure complexity.

However, the optimal design is not a fixed combination of mechanical application. In practical engineering, it is necessary to make fine adjustment based on this principle:When the clear height of the building is limited, the stiffness loss caused by reducing the height span ratio can be compensated by using parabolic form or slightly increasing the angle of the web member;For dynamic loads, it is necessary to appropriately increase the height span ratio and strengthen the joint structure. This "flexible adaptation under the guidance of principles" is the core wisdom of balancing theoretical optimization and engineering practice.

Therefore, Excellent truss design follows clear optimization levels. First, the optimal structural form is selected according to the span and load, then the collaborative parameter benchmark combination is determined, and finally the precise adjustment is made for the specific constraints, so as to achieve a precise balance between structural safety, economy and building function.

4. Conclusion

In this paper, a set of optimization method of plane truss selection based on mechanical properties is proposed, and the influence of key design parameters such as height span ratio, web member angle and vertical member setting on structural performance is systematically defined. The effectiveness and practical value of this method are verified by a specific engineering case. The research shows that, compared with the traditional experience based design method, the data-driven optimization design method can significantly improve the material efficiency and structural performance on the premise of ensuring the structural safety. The engineering practice shows that the material consumption can be reduced by 12% to 18% on average, and the structural stiffness can be increased by more than 25%, which realizes the collaborative optimization of economic benefits and mechanical properties, and provides a clear theoretical basis and feasible technical path for the scientific selection and fine design of plane truss.

However, the current research is still mainly focused on the conventional symmetrical geometry under static load, and its application scenarios have certain limitations. In order to expand the applicable boundary of the optimization method and improve its design efficiency, future work can be deepened in multiple dimensions. First of all, the research scope should be extended from static load to dynamic load cases such as wind-induced vibration and earthquake, and complex geometric forms such as asymmetry and curve shape should be considered to meet more diversified actual engineering needs. Secondly, it is suggested to introduce intelligent optimization algorithms such as neural network to build an automatic optimization design process oriented by multi-objective, such as material consumption, stiffness and construction convenience, so as to greatly improve the design efficiency and global optimization of the scheme under complex conditions. Finally, by building an integrated design platform integrating parametric modeling, intelligent algorithm optimization and rapid performance evaluation, the plane truss design can be promoted to a new stage of data-driven and performance priority intelligence.

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