

Article

Safety Design of Rotary Drilling Rig Mast Based on Multi-Condition Analysis

Heng Yang *, Yuhang Ren, Haorong Yang and Gening Xu

College of Mechanical Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, China; s202212210256@stu.tyust.edu.cn (Y.R.); s202312210206@stu.tyust.edu.cn (H.Y.); 1982036@tyust.edu.cn (G.X.)

* Correspondence: hengyang2008024@outlook.com

Abstract: To achieve both safety and a lightweight design for rotary drilling rig masts, this study proposes an optimization method incorporating safety evaluation constraints. The method employs the limit state method to validate the mast structure and uses fuzzy comprehensive evaluation to quantify safety performance metrics. The optimization objective is to minimize the mast's self-weight, with design variables defined as the geometric dimensions of key cross-sections, while imposing constraints on the strength, stiffness, stability, and safety scores. The safety score utilizes fuzzy comprehensive evaluation and a weighted aggregation method, considering indicators such as strength, stiffness, stability, and fatigue strength. An improved Salp Swarm Algorithm is utilized to execute the optimization process. Engineering case studies demonstrate that the optimized design reduces the mast's self-weight by 6.5% under safety constraints. Compared to designs without safety constraints, the material usage increases slightly by 7.3%, but the safety performance improves by 14.74%. The findings indicate that integrating safety evaluation constraints into the optimization process not only enhances the structural safety of the mast but also achieves a favorable balance between safety and economic efficiency. This approach provides a valuable reference for the safety-focused design of rotary drilling rig masts.

Keywords: rotary drilling rig mast; optimization design; safety evaluation; improved Salp Swarm Algorithm; fuzzy comprehensive evaluation



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1. Introduction

The rotary drilling rig is a large-scale engineering machine widely used in foundation construction for high-rise buildings, bridges, and infrastructure pile foundations. As a critical component of the rotary drilling rig, the mast bears the drilling and lifting loads, making it a key structural element. Its design quality directly influences the operational efficiency and safety of the equipment. Therefore, conducting reliable safety design for the mast holds significant research value and practical importance for ensuring engineering safety.

Numerous scholars have conducted research on structural optimization in the following areas. Wang et al. [1] optimized the main beam of double-beam bridge cranes by addressing redundancy and resonance. Using six key parameters and an improved particle swarm optimization algorithm, they enhanced stability, increased the first-order vibration frequency from 18 Hz to 27.55 Hz, and reduced the beam's weight by 6%. Qi et al. [2] proposed a green design method for cranes, using optimization models and fuzzy mathematics to reduce weight and processing waste. The method achieved a 63.43% reduction

in waste and a 27.03% decrease in girder cross-sectional area. Yu et al. [3] proposed an equal-life, lightweight design for crane girders using machine learning and optimization, achieving an improved life distribution and reduced weight for enhanced performance. Ren et al. [4] optimized crane box girder mass by focusing on stiffener dimensions, placement, and constraints on stresses and deformations. Using ANSYS APDL and multiple optimization methods, they validated results against other algorithms, achieving optimal structural performance and reduced mass. Qu et al. [5] proposed the ACAM algorithm for crane metal structure optimization, combining ant colony and mutation-based local search. The Ant Colony Algorithm with Mutation-based Local Search (ACAM) algorithm outperformed the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) approaches, achieving a 22.23% reduction in the objective function, making it a superior optimization method. Dörterler et al. [6] applied a Grey Wolf Optimizer (GWO) to optimize the weight of spur gears, achieving a lighter design compared to previous studies. This study demonstrates the GWO's successful application in gear weight optimization for the first time. Li et al. [7] developed a rapid lightweight design system for cranes, integrating parameterization, lightweight optimization, and a two-step optimization method. The system reduced the portal's mass by 10.5% while maintaining allowable stress and strain, significantly shortening design time and reducing calculation efforts. Kulka et al. [8] optimized the box structure of overhead crane girders using MS Excel and SolidWorks 2023, reducing weight and improving stability, demonstrated through a 50-ton crane case study. Qi et al. [2] proposed a multi-objective optimization approach for crane design, focusing on minimizing both weight and manufacturing waste. By leveraging computational intelligence and fuzzy mathematics, the method achieved a 63.43% reduction in processing waste and a 27.03% decrease in the girder cross-sectional area. Okasha et al. [9] proposed a multi-objective bridge design optimization method based on system reliability, using the MSR method and NSGA-II. The approach efficiently calculates system reliability and optimizes linked-discrete design variables, as demonstrated by redesigning an actual bridge and comparing it with traditional methods. Wang et al. [10] proposed a function integration approach for lightweight design systems, addressing functional conflicts between systems through axiomatic design. Using design matrices, the relationships of design parameters are analyzed and design concepts are evaluated by combining axiomatic design with the design structure matrix.

Safety assessment involves analyzing potential risk factors to evaluate the safety of systems or structures, identify hazards, and ensure the safety of personnel and the environment. It typically combines quantitative analysis with qualitative judgment. Zhu et al. [11] developed a crane safety assessment method combining the cloud model and ICWGT, balancing expert experience with data. Applied to a shipyard portal crane, it accurately reflects safety levels. Sadeghi et al. [12] reviewed crane safety literature using 59 risk factors from CORD, identifying eight key gaps critical for improving crane management and guiding future research. Li et al. [13] proposed a crane safety assessment method integrating entropy and cumulative prospect theory, effectively addressing inaccuracies. The method evaluates four crane samples, demonstrating its precision and feasibility. Li et al. [14] introduced an improved Variable Fuzzy Sets (IVFS) method with normal membership functions to simplify crane safety evaluation when criteria are interval-based. Applied to numerical cases, the method demonstrated its effectiveness and practicality. Barozzi et al. [15] proposed an alternative methodology for assessing old timber structures, moving beyond traditional concepts like "Knowledge Level" and "Confidence Factor". Experimental data from timber joists were used to support the approach. Ruud et al. [16] applied the IMO's formal safety assessment (FSA) to develop risk-based rules for offshore crane systems, proposing a cost-benefit method for target reliability and a framework for risk-based

rules. Zhang et al. [17] developed a safety evaluation system for quayside container crane structures, introducing the “0–4” scoring method combined with fuzzy comprehensive evaluation (04-FCE). The approach assesses safety levels, offers risk reduction suggestions, and is validated through case analysis.

Existing optimization designs primarily focus on ultimate load conditions, with limited attention given to safety evaluation, resulting in lower safety levels in optimization outcomes. This deficiency could lead to structural failures, posing risks to personnel safety. This study proposes a multi-condition safety design methodology for rotary drilling rig masts. The approach employs cross-sectional parameters as optimization variables and aims to minimize cross-sectional area while considering constraints such as strength, stiffness, stability, fatigue, and safety evaluation. Safety evaluation is conducted by constructing a fuzzy analytic hierarchy model to comprehensively assess safety performance under multiple working conditions, considering safety evaluation indicators such as strength, stiffness, stability, and fatigue strength. The proposed method enables a thorough quantitative analysis of the mast’s safety performance and is validated through practical case studies, demonstrating the effectiveness of the evaluation system.

2. Classification of Working Conditions and Structural Mechanics Model

The main components of a rotary drilling rig include the chassis, undercarriage, mast, drill rods, drill bit, and power head, as illustrated in Figure 1. This study focuses on the mast, which is an essential component of the rotary drilling rig. It not only provides guidance for the drilling tools but also plays a critical role in support and load-bearing. As the primary executing mechanism of the rotary drilling rig, the performance and stability of the mast directly impact the operational efficiency and safety of the entire machine [18].

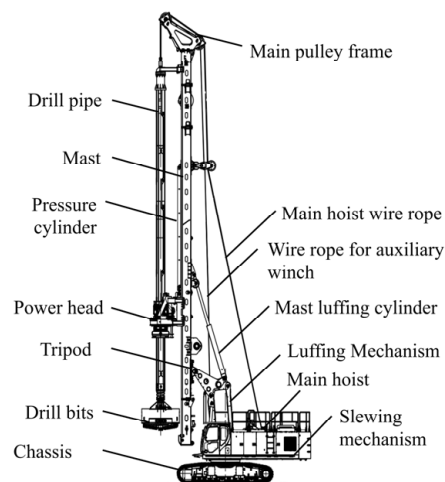


Figure 1. Rotary drilling rig.

2.1. Classification of Operating Conditions

This study primarily analyzes the working environment and workflow of the rotary drilling rig. Based on the operational principles of the rotary drilling rig, its working conditions are classified into seven typical scenarios: the drilling condition (B1), lifting condition (B2), in-hole lifting condition (B3), spoil discharging condition (B4), soil shaking condition (B5), traveling condition (B6), and rotation condition (B7), as shown in Table 1.

Table 1. Working conditions.

Labels	Working Condition	Clarification
B1	Drilling Condition	The working principle of the rotary drilling rig under the drilling condition is as follows: the power head provides torque to the drill rod and drill bit, while the pressure cylinder applies downward force, enabling the drill rod and bit to penetrate the ground and advance drilling operations [19].
B2	Out-of-Hole Lifting Condition	The working principle of the rotary drilling rig under the lifting condition outside the hole is as follows: the main hoist lifts the drill rod and bit to the ground surface, while the weight of the power head is supported by the pressure cylinder [19].
B3	In-Hole Lifting Condition	The working principle of the rotary drilling rig under the in-hole lifting condition is as follows: the main hoist incrementally lifts the drill rod and bit within the borehole using a wire rope.
B4	Dumping Condition	The working principle of the rotary drilling rig in the dumping condition is as follows: the power head drives the drill rod in alternating forward and reverse rotations to release the soil.
B5	Shaking Condition	The working principle of the rotary drilling rig in the shaking condition is as follows: the main hoist undergoes continuous start-stop cycles, allowing the drill rod and bit to move up and down. This process utilizes inertia to release soil from the drill.
B6	Traveling Condition	The working principle of the rotary drilling rig in the walking condition is as follows: the drill rod is fully retracted and the mast is raised to its upper position, allowing the rig to move to the next drilling site.
B7	Rotation Condition	The working principle of the rotary condition is as follows: the drill rod is retracted and the upper structure of the rig rotates relative to the chassis.

2.2. Mechanical Model

The mechanical models of the rotary drilling rig can be classified into two typical types: the drilling model and the lifting model. The differences between operating conditions are primarily reflected in variations in dynamic load coefficients and the magnitude of the applied loads. The following sections will introduce these two models in detail.

2.2.1. Drilling Mechanical Model

In the drilling mode, the forces and constraints acting on the mast are shown in Table 2. The force diagram is illustrated in Figure 2. Based on the force state diagram, the external force equilibrium equations can be established for calculations and the corresponding internal force diagrams can be drawn to facilitate a deeper analysis of the mechanical properties.

Table 2. Forces and constraints under drilling condition.

Force	Constraint
the weight of the mast	the large disc is fixed at the hinge support
the rotary disk's deadweight	
the main pulley frame	
the back wheel's deadweight	
the torque of the power head	the inclined cylinder is connected via a movable hinge
the pressure cylinder pressurization	
the wind load	

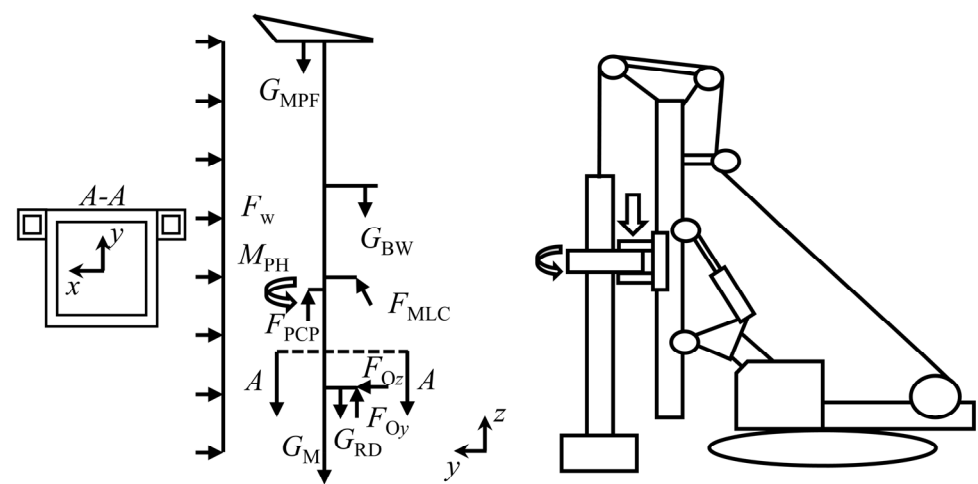


Figure 2. Drilling model.

2.2.2. Lifting Mechanical Model

In the lifting condition, the forces and constraints acting on the mast are shown in Table 3.

Table 3. Forces and constraints under lifting condition.

Force		Constraint	
the weight of the mast	G_M	the large disc is fixed at the hinge support	F_{Oz}
the rotary disk's deadweight	G_{RD}		F_{Oy}
the main pulley frame	G_{MPF}		
the back wheel's deadweight	G_{BW}		
the self-weight of the power head	G_{PH}	the inclined cylinder is connected via a movable hinge	F_{MLC}
the self-weight of the pressurized cylinder	G_{PC}		
the wind load	F_w		
the lifting force of the main winch	F_T		

The force diagram is shown in Figure 3.

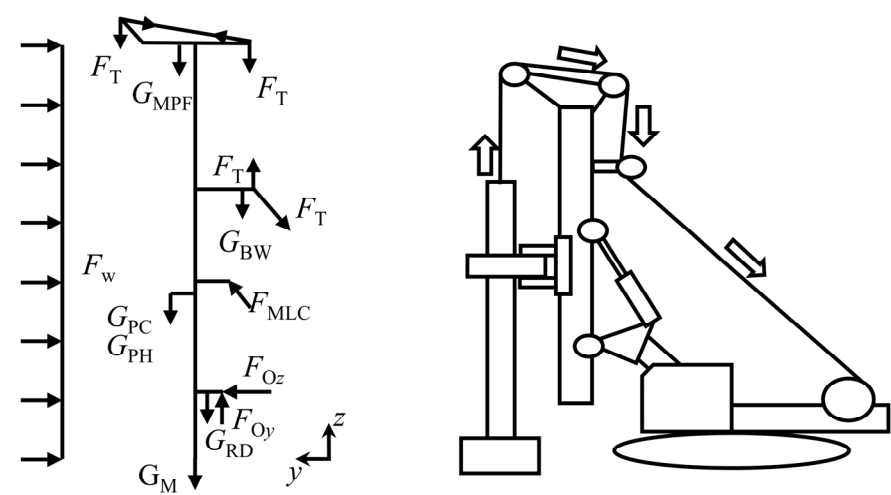


Figure 3. Lifting model.

2.3. Load-Bearing Capacity Analysis

Based on the two typical mechanical models described above, this study conducts an evaluation of the load-bearing capacity. In the lifting condition, the drilling mast is considered an eccentrically loaded column, whereas in the drilling condition influenced by

the pressure cylinder, the mast is analyzed as a tension member. Therefore, it is necessary to verify the load-bearing capacities of these two extreme conditions separately. According to engineering experience, the cross-section of the large disc is selected as the critical section for analysis [20]. Subsequently, an analysis is conducted at the critical points. Points 1 and 3 are subjected to the maximum bending stresses along the x -axis and y -axis directions, while points 2 and 4 are located at the intersection of the midlines of the box-shaped section, resulting in a more complex stress state characterized by spatial stress conditions, as illustrated in Figure 4.

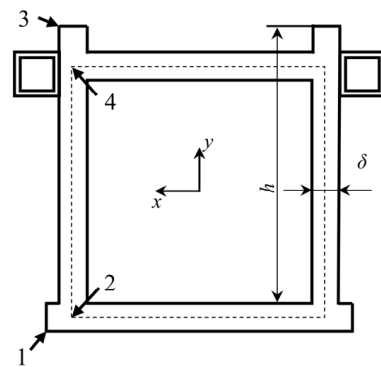


Figure 4. Critical points.

2.3.1. Strength Analysis

- Drilling Model

In the drilling condition, the cross-section is subjected to axial forces, shear forces, bending moments, and torques, resulting in a complex stress state, as illustrated in Figure 5.

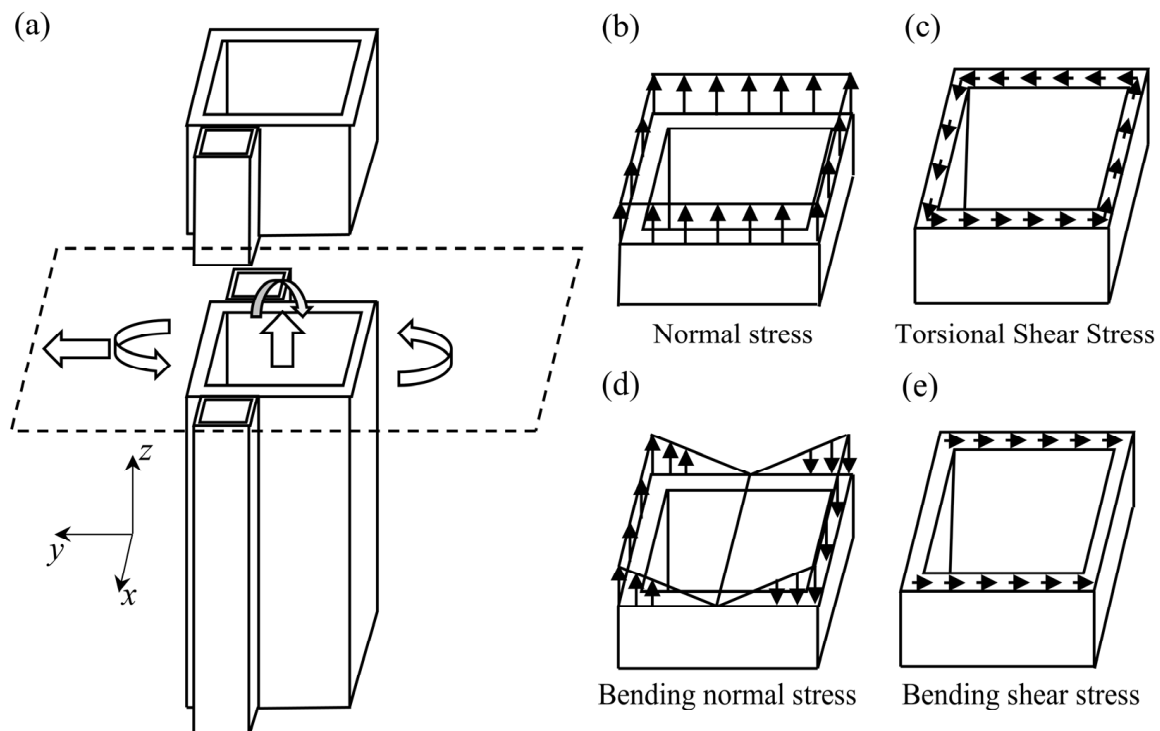


Figure 5. Drilling conditions: (a) internal forces in the cross-section; (b) cross-sectional normal stress distribution; (c) cross-sectional torsional shear stress distribution; (d) cross-sectional bending normal stress distribution; and (e) cross-sectional bending shear stress distribution.

During the pressurized drilling phase with the hydraulic cylinder, the drilling mast acts as a tension member. The formula for calculating the normal stress [21] is given in Equation (1).

$$\sigma_{B1} = \frac{N}{A_j} + \frac{M_x}{W_{jx}} + \frac{M_y}{W_{jy}} \quad (1)$$

In the equation, N represents the axial force on the calculated cross-section; A_j denotes the net cross-sectional area of the member; and M_x and M_y are the bending moments about the x -axis and y -axis at the calculated cross-section, respectively. The moment about the x -axis primarily originates from the moment generated by the applied or lifting force acting on the centroid, while the y -axis primarily arises from the eccentric load of the main pulley frame; and W_{jx} and W_{jy} are the section modulus for bending about the x -axis and y -axis for the net cross-sectional area of the member. For box-section structures, the constrained bending stress should be calculated. To simplify, a coefficient method is used, taking it as 0.1 times the free bending stress.

In addition, it is also subjected to bending shear stress, which is calculated using the following formula, as shown in Equation (2):

$$\tau_s = \frac{F}{(2 \times h \times \delta)} \quad (2)$$

In the equation, F represents the shear force; h is the height of the web; and δ denotes the thickness of the web.

In addition to the aforementioned normal stress and shear stress due to bending, the section under pressurized drilling also experiences torque. The simplified calculation formula for the torsional shear stress is given by Equation (3) as follows:

$$\tau_n = \frac{T_n}{(2 \times A_0 \times \delta_{\min})} \quad (3)$$

In the equation, A_0 represents the area enclosed by the midline of the closed section plate thickness, while $\delta_{\min}$ denotes the minimum plate thickness of the section.

Due to constrained torsion, both sector shear stress and sector normal stress are present. The sector shear stress is generally negligible compared to the torsional shear stress. For the sector normal stress, a coefficient method is applied, assuming it to be 0.05 times the free bending normal stress.

The types of stress at the critical points are shown in Table 4.

Table 4. Types of stress at critical points under drilling conditions.

Section	Stress Categories	Formula	Point 1	Point 2	Point 3	Point 4
Critical Section	Normal Stress	(1)	✓	✓	✓	✓
	Constrained Bending Normal Stress			✓		✓
	Constrained Torsional Normal Stress			✓		✓
	Bending Shear Stress	(2)		✓		✓
	Torsional Shear Stress	(3)		✓		✓

For points 2 and 4, which are under a three-dimensional stress state, it is necessary to calculate the von Mises stress to convert the three-dimensional stress state into a uniaxial stress state, as shown in Equations (4) and (5).

$$\sigma = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} \quad (4)$$

$$\sigma_{r4} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]} \quad (5)$$

In Equation (4), the subscripts 1, 2, and 3 denote the principal stresses, which represent the normal stresses acting on the principal planes where shear stress is zero.

- Lifting Model

For the inner lifting condition, the drill mast behaves as an eccentric compression member, subjected to axial force, shear force, and bending moment, as illustrated in Figure 6.

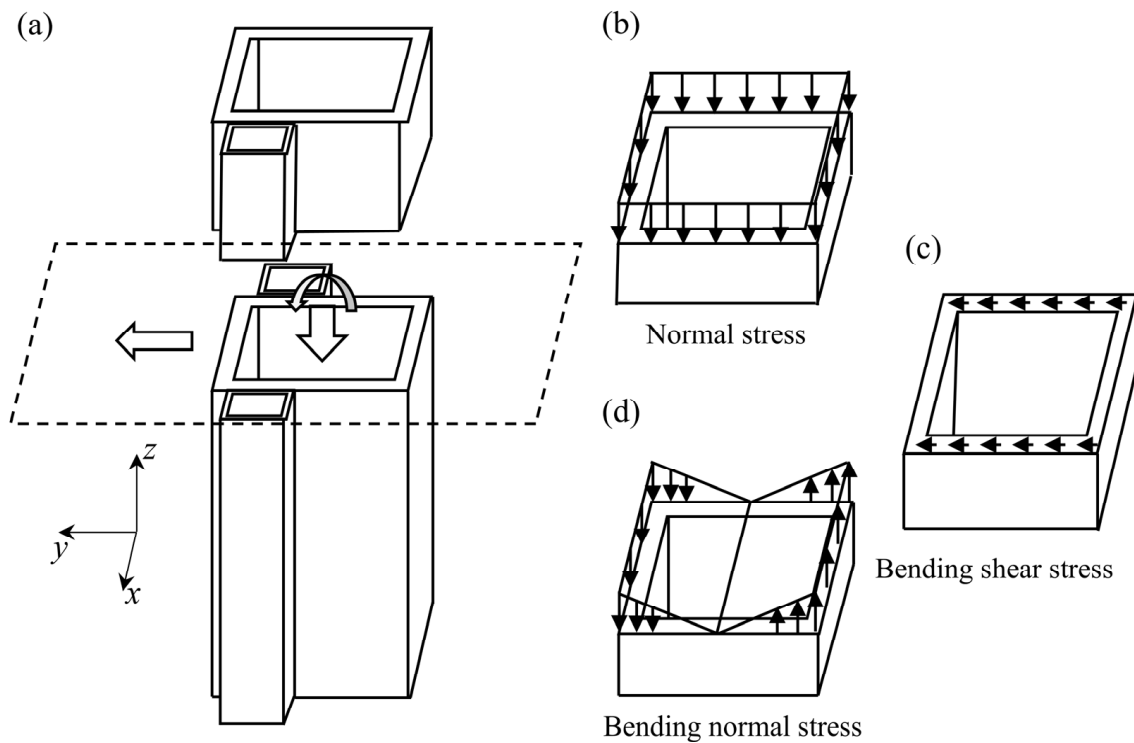


Figure 6. In-hole lifting conditions: (a) internal forces in the cross-section; (b) cross-sectional normal stress distribution; (c) cross-sectional bending shear stress distribution; (d) cross-sectional bending normal stress distribution.

For the inner lifting condition, the limit compression of the rotary drilling rig mast is characterized as a compressive-bending member. The axial stress is given by Equation (6):

$$\sigma_{B3} = \frac{N}{A_j} + \frac{M_x}{(1 - (N/N_{Ex}))W_{jx}} + \frac{M_y}{(1 - (N/N_{Ey}))W_{jy}} \quad (6)$$

In the equation, N_{Ex} and N_{Ey} represent the nominal critical Euler force of the member, as defined in Equation (7). When $N/N_E < 0.1$, the axial stress can be calculated using Equation (1), with the remaining parameters as described above.

$$N_{Ex,y} = \frac{\pi^2 EA}{\lambda_{x,y}^2} \quad (7)$$

In addition, it is also subjected to bending shear stress, the calculation formula for which is given in Equation (2).

The stresses experienced by the critical points of the dangerous section of the drill mast are shown in Table 5.

Table 5. Types of stress at critical points under in-hole lifting conditions.

Section	Stress Categories	Formula	Point 1	Point 2	Point 3	Point 4
Critical Section	Normal Stress	(6)	✓	✓	✓	✓
	Constrained Bending Normal Stress			✓		✓
	Bending Shear Stress	(2)		✓		✓

2.3.2. Stiffness Analysis

In engineering, the slenderness ratio is commonly used to check stiffness, as shown in Equation (8):

$$\lambda = l_0/r \leq [\lambda] \quad (8)$$

In the equation, λ is the slenderness ratio of the member. l_0 represents the effective length, $l_0 = \mu_1 l$. r denotes the minimum radius of gyration of the gross cross-section, $r = \sqrt{I/A}$. $[\lambda]$ is the allowable slenderness ratio.

2.3.3. Overall Stability

The column is a thin-walled structure. To ensure its safe and normal operation, it is essential to guarantee not only the strength and stiffness of the column but also its stability. Therefore, a stability analysis of the column is necessary [22]. Based on the most critical load condition, which is the internal lifting condition under compression, its overall stability is assessed using the following Equation (9):

$$\frac{N}{\varphi A} + \frac{M_x}{(1 - (N/N_{Ex}))W_x} + \frac{M_y}{(1 - (N/N_{Ey}))W_y} \leq [\sigma] \quad (9)$$

In the equation, N represents the axial force; φ is the stability coefficient; A denotes the gross cross-sectional area of the member; M_x and M_y are the primary bending moments about the x -axis and y -axis, respectively; and W_x and W_y are the section modulus for bending about the x -axis and y -axis, respectively. For the axial force and uniformly distributed weight acting at the midspan of the member, an equivalent force needs to be applied at the top end of the drilling mast.

2.3.4. Fatigue Strength

The fatigue strength verification formula [23,24] is shown in Equation (10). The left-hand side of the equation represents the stress range under a typical working cycle [25], while the right-hand side indicates the limit design stress range represented by the stress history parameters, considering the working grade.

$$\sigma_{\max} - \sigma_{\min} \leq \frac{\Delta\sigma_c}{(\gamma_{mf} \sqrt[3]{sm})} \quad (10)$$

In the equation, $\sigma_{\max}$ and $\sigma_{\min}$ are the partial safety factors, considering the dynamic load coefficient in the design stress limit. $\Delta\sigma_c$ represents the characteristic fatigue strength, defined as the fatigue strength under a constant stress range, corresponding to 2×10^6 cycles with a reliability probability of 97.7%. γ_{mf} is the fatigue strength resistance coefficient and s_m is the stress history parameter.

3. Fuzzy Comprehensive Evaluation

The mast structure of a rotary drilling rig is a critical component and its performance directly affects the operational efficiency and safety of the entire machine. Due to the inherent randomness in the evaluation process, the assessment of the mast structure

involves a high degree of uncertainty. As a result, fuzzy comprehensive evaluation [26,27] has emerged as an effective solution.

The safety evaluation model for the mast's metal structure consists of three main components: the evaluation system, the membership degree matrix, and the weight vector. The overall process is shown in Figure 7. First, safety indicators are determined based on the factors influencing safety and the corresponding indicator layers and rating systems are established. Next, the membership degrees between the indicators and the evaluation categories are calculated using membership functions. Then, the Analytical Hierarchy Process (AHP) and the CRITIC method are applied to weight the indicators. Finally, the fuzzy comprehensive evaluation result is obtained by performing a dot product operation between the membership degree matrix and the weight vector.

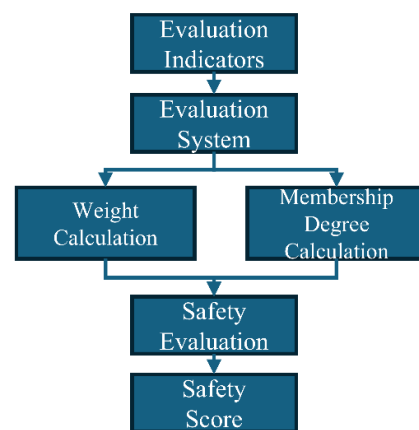


Figure 7. Evaluation Process.

3.1. Evaluation System

For the safety assessment of the rotary drilling rig mast, an evaluation system is constructed, consisting of a goal layer and an indicator layer, as shown in Figure 8. The goal layer represents the “Metal Structure Safety Assessment of the Mast”, which is the core objective of the comprehensive evaluation. The indicator layer includes four key indicators: strength, stiffness, stability, and fatigue. These indicators are considered inverse indicators, meaning that the smaller the indicator value, the higher the safety performance.

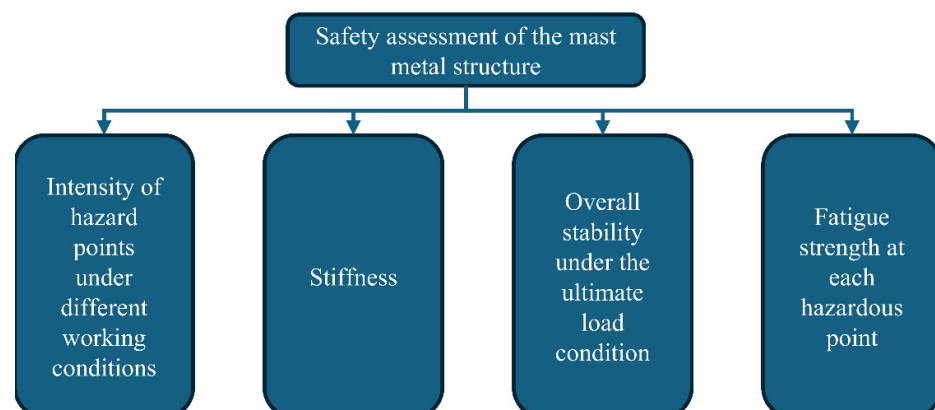


Figure 8. Evaluation system.

3.2. Quantification Mechanism of Safety Indicators

The membership matrix reflects the fuzzy mapping relationship between each indicator and the corresponding evaluation comments. Commonly used methods for calculating membership include fuzzy statistical methods, membership functions, and subjective

experience-based methods. The fuzzy statistical method requires a large amount of data samples, while the subjective experience-based method introduces a strong degree of subjectivity. Therefore, this study selects the trapezoidal membership function, which offers higher objectivity, to calculate the membership degree. The evaluation set consists of four levels, denoted as $G = \{G_1, G_2, G_3, G_4\}$, where G_1 to G_4 correspond to the four levels of “poor”, “fair”, “good”, and “excellent”, respectively. The range of the evaluation set is shown in Table 6.

Table 6. Range boundaries of evaluation criteria for each indicator layer.

	b_1^g	b_2^g	b_3^g	b_4^g
Static Strength				
Stiffness				
Overall Stability	Poor Value	Medium Value	Good Value	Excellent Value
Fatigue Strength				

The indicators in this study are all inverse indicators, and the specific trapezoidal membership function calculation formulas are shown in Table 7.

Table 7. The trapezoidal membership function calculation formulas.

Poor	Fair	Good	Excellent
$\begin{cases} m_{g1} = 1, & y_g \leq b_1^g \\ m_{g1} = \frac{b_2^g - y_g}{b_2^g - b_1^g}, & b_1^g \leq y_g \leq b_2^g \\ m_{g1} = 0, & y_g > b_2^g \end{cases}$	$\begin{cases} m_{g2} = 1, & y_g \leq b_1^g \\ m_{g2} = \frac{y_g - b_1^g}{b_2^g - b_1^g}, & b_1^g \leq y_g \leq b_2^g \\ m_{g2} = \frac{b_3^g - y_g}{b_3^g - b_2^g}, & b_2^g \leq y_g \leq b_3^g \\ m_{g2} = 0, & y_g > b_3^g \end{cases}$	$\begin{cases} m_{g3} = 0, & y_g \leq b_2^g \\ m_{g3} = \frac{y_g - b_2^g}{b_3^g - b_2^g}, & b_2^g \leq y_g \leq b_3^g \\ m_{g3} = \frac{b_4^g - y_g}{b_4^g - b_3^g}, & b_3^g \leq y_g \leq b_4^g \\ m_{g3} = 0, & y_g > b_4^g \end{cases}$	$\begin{cases} m_{g4} = 1, & y_g \leq b_3^g \\ m_{g4} = \frac{y_g - b_3^g}{b_4^g - b_3^g}, & b_3^g \leq y_g \leq b_4^g \\ m_{g4} = 0, & y_g > b_4^g \end{cases}$

3.3. Method of Weight Assignment

In the evaluation process, the values reflecting the relative importance of each indicator are referred to as weights. In a fuzzy comprehensive evaluation system, indicators at different levels have varying degrees of importance. Assigning appropriate weight values to each indicator based on its significance directly influences the accuracy of the evaluation results. There are three primary methods for weight assignment: subjective weighting, objective weighting, and combined weighting. Selecting the appropriate weight assignment method based on specific circumstances helps to enhance the authenticity and validity of the evaluation results. For the safety assessment of the rotary drilling rig mast, this study adopts a combined weighting approach that integrates both subjective and objective methods for weight assignment.

3.3.1. Analytic Hierarchy Process

The subjective weighting method includes techniques such as the Delphi method and Analytic Hierarchy Process (AHP). In this study, the Analytic Hierarchy Process is chosen. The AHP is a method that decomposes a complex decision system into hierarchical levels, such as goals, criteria, and alternatives, to establish a relevant model. Based on this structure, the AHP combines both qualitative and quantitative analyses for systematic decision evaluation. This method is characterized by its clear structure, strong flexibility, and ease of implementation.

When applying the AHP for weight assignment, the first step is to perform pairwise comparisons of the evaluation criteria based on their relative importance and construct the judgment matrix A (see Equation (11)), as shown in Table 8.

Table 8. Judgment matrix scale.

Scale	Implication
1	Equally important
3	Slightly more important
5	Significantly more important
7	Very important
9	Extremely important

Then, the consistency of the judgment matrix is checked using Equations (12) and (13) to ensure the rationality of the weight allocation.

$$A = \begin{vmatrix} 1 & a_{12} & a_{13} & a_{14} \\ 1/a_{12} & 1 & a_{23} & a_{34} \\ 1/a_{13} & 1/a_{23} & 1 & a_{34} \\ 1/a_{14} & 1/a_{34} & 1/a_{34} & 1 \end{vmatrix} \quad (11)$$

In the equation, a_{12} represents the relative importance of the first indicator compared to the second indicator.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (12)$$

$$CR = \frac{CI}{RI} \quad (13)$$

In the equation, $\lambda_{\max}$ represents the maximum eigenvalue of the judgment matrix; n denotes the number of indicators; CI is the consistency index; RI is the average random consistency index, with values shown in Table 9; and CR is the consistency ratio.

Table 9. The average consistency index.

Number of Indicators	3	4	5	6	7
RI	0.539	0.916	1.143	1.292	1.375

When the consistency check is satisfied for $CR < 0.1$, the eigenvector corresponding to the largest eigenvalue of the judgment matrix is normalized to obtain the weights of the indicators.

3.3.2. CRITIC Method

Common objective weighting methods include the entropy method [28], CRITIC method [29], and others. In this study, the CRITIC method is adopted. The CRITIC method is a weighting decision technique based on objective data and scientific analysis. This method objectively evaluates and quantifies the importance of each evaluation indicator to determine the weight of each indicator in the final evaluation or decision. The calculation process is as follows:

1. First, construct the evaluation matrix. Supposing there are several elements and multiple evaluation indicators, an evaluation matrix can be constructed based on this information, as shown in Equation (14).

$$B = \begin{pmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mn} \end{pmatrix} \quad (14)$$

2. Next, perform standardization on the input matrix as shown in Equation (15), denoted as the standard matrix. This operation normalizes the original matrix into a standardized form.

$$c_{ij} = \frac{b_{ij}}{\sqrt{\sum_{j=1}^n b_{ij}^2}} \quad (15)$$

3. Finally, based on the standardized matrix, calculate the standard deviation s_j of each indicator (see Equation (16)), the correlation coefficient r_{ij} between each pair of indicators (see Equation (17)), and the potential conflict indicator e_j (see Equation (18)). The weight of each indicator can then be calculated as shown in Equation (19).

$$s_i = \sqrt{\frac{\sum_{i=1}^n (\bar{c}_i - c_{ij})^2}{m-1}} \quad (16)$$

$$r_{ij} = \frac{\text{cov}(c_i, c_j)}{s_i s_j} \quad (17)$$

$$e_i = \sum_{i=1}^m (1 - r_{ij}) \quad (18)$$

$$\omega_i = \frac{s_i e_i}{\sum_{i=1}^m s_i e_i} \quad (19)$$

In the equation, $\bar{c}_i$ represents the average value of the elements in the i -th row of the standardized matrix; $\text{cov}(c_i, c_j)$ denotes the covariance between the i -th and j -th rows of the matrix.

3.3.3. Weight Combination

In this study, the subjective and objective weights are combined using a linear aggregation method, as shown in Equation (20).

$$w = \alpha w_{\text{ahp}} + (1 - \alpha) w_{\text{critic}} \quad (20)$$

In the equation, w represents the composite weight, w_{ahp} denotes the subjective weight, w_{critic} represents the objective weight, and α is the weight of the subjective weight relative to the objective weight, which is set to 0.5 in this study.

3.4. Comprehensive Safety Evaluation

Once the membership matrix MM is obtained, the fuzzy comprehensive evaluation matrix $FCEM$ can be derived by performing a dot product operation with the weight vector w , as expressed in Equation (21). To make the evaluation results more intuitive, this study assigns specific scores to each grade in the evaluation set $G = \{G_1, G_2, G_3, G_4\}$. The corresponding score vector is $GS = [40, 60, 80, 100]$. The safety evaluation score is then calculated using Equation (22).

$$FCEM = w \cdot MM \quad (21)$$

$$SAS = FCEM \cdot GS^T \quad (22)$$

4. Optimization Model and Algorithm

Optimization design involves constructing a mathematical model to describe the optimization problem. Based on the research presented in the previous two chapters, this study employs an improved Salp Swarm Algorithm [25] for structural optimization.

4.1. Optimization Model

To address the issue of low reliability in optimization results, this study incorporates a safety evaluation constraint in addition to the conventional load-bearing capacity constraint. This enhancement improves the safety of the optimization outcomes. The optimization model is defined as shown in Equation (23).

$$\begin{aligned} \min f(x_1, x_2, x_3, x_4) &= x_1 \times x_2 - (x_1 - x_3) \times (x_2 - x_4) + A \\ \text{s.t.} \begin{cases} G_i(x) \leq 0; & i = 1, \dots, 5, \\ lb \leq x_i \leq ub & i = 1, 2, \end{cases} \end{aligned} \quad (23)$$

In the equation, f represents the objective function, which is the cross-sectional area. x_1 – x_4 are the optimization design variables, where x_1 denotes the width of the cross-section, x_2 the height of the cross-section, x_3 twice the thickness of the web, and x_4 twice the thickness of the flange. A is the fixed area. G_i represents the constraints, as detailed in Table 10.

Table 10. The constraint conditions.

	Name	Formula	Descriptive
1	Variable upper and lower bound constraints	$lb \leq x_i \leq ub$	The variables can take values within the specified upper and lower bounds.
2	Strength	$\sigma_{B1} \leq \lim \sigma, \sigma_{B3} \leq \lim \sigma$	The stress under the maximum loading condition must be less than the stress limit.
3	Stiffness	$\lambda \leq [\lambda]$	The maximum slenderness ratio must be less than the allowable slenderness ratio.
4	Overall stability	$\sigma_{os} \leq \lim \sigma$	The overall stability must be less than the allowable limit value.
5	Fatigue Strength	$\Delta \sigma \leq \lim \Delta \sigma$	The maximum range of calculated design stress must be less than the range of the design stress limit.
6	Safety evaluation	$SAS \geq 80$	Each working condition must undergo a safety assessment, ensuring that the overall safety score is no less than 80.

4.2. Improved Salp Swarm Algorithm

For the structural optimization problem, this study utilizes the improved Salp Swarm Algorithm to perform optimization. This approach yields higher-quality solutions with advantages such as faster iteration speed and stronger robustness. The thickness of the web plate and flange plate are selected from a set of standard thickness values and combinations of the thicknesses form a dimension. This process generates multiple dimensions to enhance the solution quality. Furthermore, improved strategies are applied within each dimension to accelerate convergence. The flowchart of this process is shown in Figure 9.

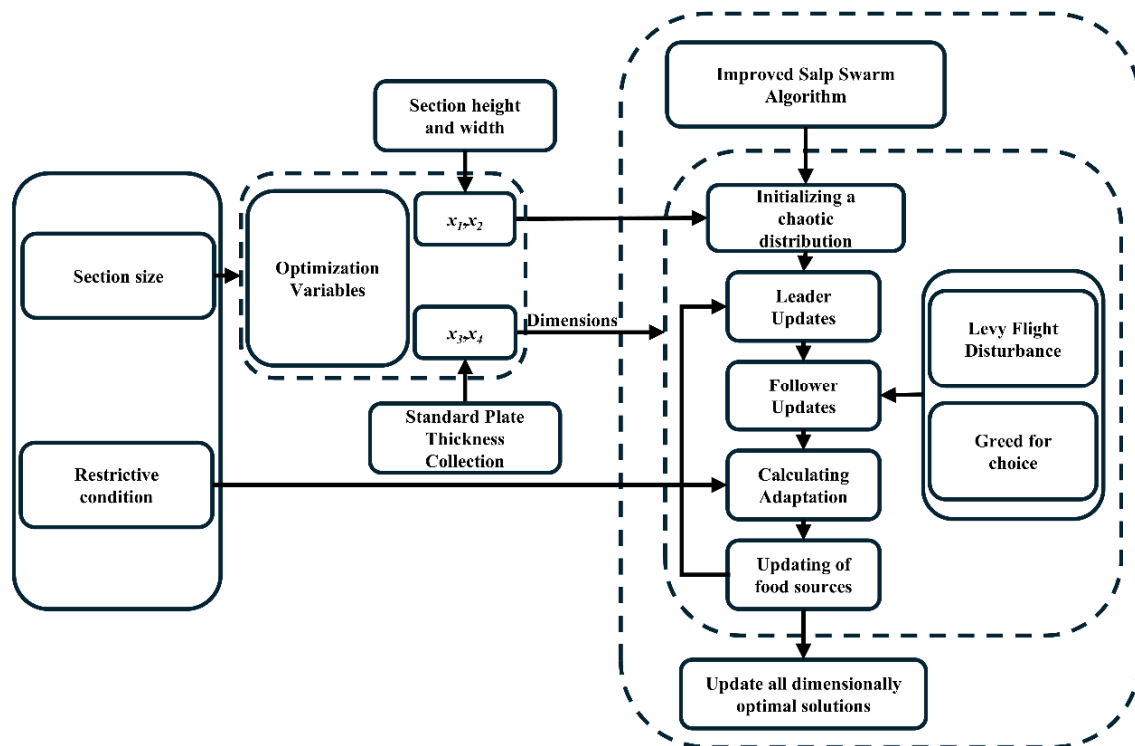


Figure 9. Flowchart of the improved Salp Swarm Algorithm.

5. Engineering Application

This study uses a specific model of a rotary drilling rig as an example to validate the effectiveness of the proposed method. The parameters of the model are shown in Table 11 below.

Table 11. Model parameters.

Parameter	Value	Unit
Maximum Output Torque	500	kN·m
Maximum Pressing Force of Pressurizing Cylinder	500	kN
Maximum Lifting Force of Pressurizing Cylinder	500	kN
Maximum Lifting Force of Main Hoist	600	kN

5.1. Load-Bearing Capacity Check and Safety Score

A judgment matrix is constructed based on the relative importance of each indicator. Since the drill mast is primarily a compression member, instability is the most critical failure mode and therefore it is assigned the highest level of importance. On the other hand, stiffness affects the quality of hole formation but has a lesser impact on personal safety, so its importance is relatively low. The corresponding judgment matrix is shown in Equation (24).

$$A = \begin{bmatrix} 1 & 3 & 1 & 1 \\ 1/3 & 1 & 1/3 & 1/3 \\ 1 & 3 & 1 & 3 \\ 1 & 3 & 1/3 & 1 \end{bmatrix} \quad (24)$$

The combined weight, derived from both subjective and objective weights, is given by the following Equation (25).

$$w = [0.24910 \quad 0.1522 \quad 0.3593 \quad 0.2394] \quad (25)$$

The boundary values of the trapezoidal membership function are shown in Table 12. Currently, there is no unified standard for setting the evaluation ranges of each indicator. Typically, it is necessary to refer comprehensively to relevant design specifications [23] and consider expert opinions to reasonably determine the range of the boundary values [30]. For example, in the case of static strength, the yield stress of the material for this machine model is 550 MPa. Based on the limit stress formula, the ultimate stress is calculated as 495 MPa and the boundary values are divided with a fixed interval of 50 MPa.

Table 12. The evaluation range boundaries.

	b_1^g	b_2^g	b_3^g	b_4^g
Static Strength	345	395	445	495
Stiffness	60	100	140	180
Overall Stability	345	395	445	495
Fatigue Strength	223	253	283	313

b_1^g , b_2^g , b_3^g , and b_4^g represent the Poor Value, Medium Value, Good Value, and Excellent Value of each indicator, respectively.

The existing load-bearing capacity and safety assessment results of the drilling mast are shown in Table 13. From the evaluation results, it can be observed that the mast has a certain safety margin in terms of load-bearing capacity, providing a solid foundation for further optimization design.

Table 13. Load-bearing capacity and safety assessment.

Parameters	Calculated Values	Limit Value	Unit
Strength	289 354	495	MPa
Stiffness	147	180	
Fatigue Strength	234	313	MPa
Nominal Euler Critical Load		4245	kN
Overall Stability	434	495	MPa
Safety Score	89.4	80	

5.2. Optimization Results

The parameters for the optimization algorithm are set as follows: the maximum number of iterations is 100, the population size is 100, and the standard plate thickness dataset is $T = [6, 8, 10, 12]$. The range of variation for the optimization variables is presented in Table 14.

Table 14. The range of variation for the optimization variables.

	x_1	x_2	x_3	x_4
Range of variation/mm	0–750	0–750	[12, 16, 20, 24]	

The results are presented in the Table 15 below.

Table 15. Comparison of optimization results.

	x_1	x_2	x_3	x_4	Objective Function	Safety Score
Original design	750	750	24	24	45,056	89.4
Optimized design	750	750	16	24	39,248	72.6
Safety-optimized design	749	749	20	24	42,108	83.3

From the table above, it can be observed that both ordinary optimization design and safety optimization design successfully reduced the cross-sectional dimensions, achieving a certain degree of structural lightweighting. However, compared to ordinary optimization design, safety optimization design resulted in a slight increase in self-weight, approximately 7.3%, but its safety score significantly improved by nearly 14.74%. This difference reflects the significant advantage of safety optimization design in balancing both lightweighting and structural safety.

Although ordinary optimization design can reduce self-weight, it may lead to higher risks due to insufficient consideration of the structural safety performance. In extreme working conditions, this could potentially pose safety hazards. On the other hand, safety optimization design, by incorporating safety assessment constraints, effectively enhances the structural safety performance, significantly reducing the potential failure risk, and provides higher reliability and practicality for the design outcome.

From the perspective of feasibility and engineering practice, safety optimization design not only achieves the lightweighting goal but also significantly improves safety performance, demonstrating exceptional potential in meeting modern engineering demands. This design approach offers valuable reference for achieving the optimization goals of rotary drilling rig masts and sets a good example for the optimization design of other structural components.

6. Conclusions

This paper proposes an optimization model that takes into account safety evaluation constraints, effectively balancing the issues of lightweighting and safety. The following conclusions can be drawn:

1. This study developed a safety evaluation system for rotary drilling rig masts which quantifies the safety score of a mast and provides a scientific basis for its design safety evaluation. The system comprehensively considers multiple factors such as strength, stiffness, stability, and fatigue, providing a holistic reflection of the mast's safety performance.
2. By incorporating safety evaluation as a constraint in the optimization design, compared to conventional optimization methods, although there is a slight increase in weight (7.3%), the safety performance is significantly improved, with the safety score increasing by 14.74%. This design approach not only meets the lightweight requirements but also ensures the structural safety of the mast, enhancing safety assurance and providing a more reliable optimization solution for the rotary drilling rig mast design. Through this optimization method, a good balance between safety and lightweight can be achieved while maintaining economic feasibility.

To further improve the reliability of the optimization results, future research could consider employing finite element methods combined with surrogate models and other related methods to address this issue.

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