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Modeling and Optimization of the Air-Supported Membrane Coal Shed Structure in Ports

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Abstract: The air-supported membrane coal shed is widely used in bulk cargo terminals. It not only effectively protects goods from adverse weather conditions but also helps reduce coal dust and harmful gas emissions, promoting the green and sustainable development of ports. However, in practical engineering, the design parameters of the coal shed are often based on experience, making it difficult to accurately assess the quality of the structural design. The flexibility of the membrane material also makes the structure susceptible to deformation or tearing. This paper mainly focuses on modeling and solving the optimization design issues of air-supported membrane coal shed structures. According to the evaluation criteria for the form of air-supported membrane coal sheds, a multi-objective structural optimization model is established to minimize the maximum stress on the membrane surface, ensure uniform stress distribution, maximize structural stiffness, and minimize costs. The study utilizes a combined optimization approach using ANSYS 19.0 and MATLAB 2016a, incorporating an improved NSGA-II algorithm program developed in MATLAB into ANSYS for structural form analysis and load calculation. The research results indicate that the optimal solution reduces the maximum stress on the loaded membrane surface by 5.36%, shortens the maximum displacement by 30.3%, and saves on economic costs by 9.85%. Compared to traditional empirical design methods, the joint use of MATLAB and ANSYS for optimization design can provide more superior solutions, helping ports to achieve environmental protection and economic efficiency goals.

Keywords: bulk cargo ports; coal shed; multi-objective structure optimization; stress analysis

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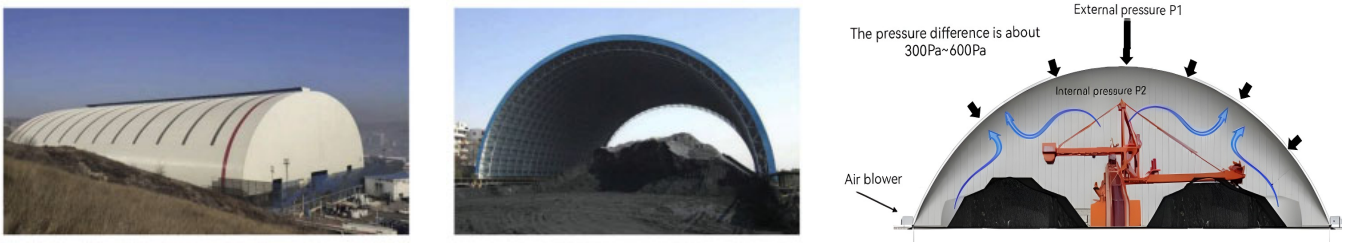
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1. Introduction

The port terminal, as an indispensable part of modern logistics, plays a crucial role in connecting land and water, facilitating efficient transportation of goods and promoting economic development. Within various types of ports, bulk cargo terminals play a vital role in handling bulk cargo. These terminals are equipped with specialized facilities and equipment to provide essential support for the loading and unloading of bulk commodities such as coal and ore [1]. However, traditional port operations often face challenges such as environmental pollution. The development of green ports requires technological infrastructure, transformation, and management to achieve sustainable development goals [2]. In this context, bulk cargo terminals are promoting the construction of coal sheds to prevent damage to coal and other commodities in harsh weather conditions, as well as to reduce dust, emissions, and waste that can pollute the environment. Depending on whether sidewalls are built, coal sheds can be classified into enclosed coal sheds (Figure 1a) and

open coal sheds (Figure 1b). Open coal sheds do not have sidewalls or only have partial sidewalls, allowing for natural ventilation to a large extent [3].



(**a**) Closed coal shed (**b**) Open coal shed (**c**) Structural principles

Figure 1. Coal shed classification and gas diaphragm coal shed structural principles.

An air-supported membrane coal shed is a type of enclosed coal shed. The structural integrity of the air-bearing membrane depends on internally pressurized air and a tensioned membrane shell (see Figure 1c for structural principles) to maintain proper size and shape [4]. Due to its excellent structural characteristics, including low cost, easy construction, and low carbon, air-supported membrane structures are widely used in sports stadiums, exhibition halls, coal sheds, and military facilities [5]. However, the membrane used in the air-supported membrane coal shed is a flexible material, which is more sensitive to the frequent large wind loads and snow loads in the port terminal. These external loads easily cause the structure to undergo large deformations, and accidents such as membrane tearing or cable network breakage even occur [6,7]. Typically, such structures must meet standards of safety and ease of maintenance, the essential elements of which include building performance, material properties, and structural behavior, to accommodate a wide range of loads and impacts [8].

Structural design optimization involves setting objective functions and constraints based on engineering requirements, adjusting structural parameters using optimization methods to achieve the optimal design. For example, Zia ur Rehman et al. [9] provide comprehensive guidance for actual construction scenarios through multi-objective optimization methods and apply response surface methods to hybrid design optimization of the proposed composite additive (CA). Zia ur Rehman and Usama Khalid [10] used the response surface method to establish a prediction model of mechanical properties and optimize the utilization of waste mask fibers. Though structural analysis software is essential for engineering calculations like stiffness, stress, and displacement, the built-in optimization algorithms may be limited. To address this, many studies now integrate custom optimization algorithms into structural analysis software for comprehensive structural optimization. Guan, B. et al. [11] proposed a non-probabilistic optimization model considering the correlation of uncertainties and established a direct solution framework that integrates a response surface model, interval analysis, and a genetic algorithm. In a study of the structural optimization of an integrated cooling system for a dome house, Mirzazade Akbarpoor, A et al. [12] carried out a 3D simulation analysis using ANSYS 19.0 FLUENT software with MATLAB 2016a modeling to explore the performance of the system as affected by geometrical and environmental parameters. Abu-Hamdeh, N.H. et al. [13] used ANSYS for the structural design of a wind turbine to simulate the structural components, and a mathematical simulation was carried out through MATLAB to create a working model of it, which was used as a basis for tests.

However, there are fewer studies on the optimal design of air-supported membrane structures, for which the structural design requires basic shape-finding analysis [14–18], structural optimization, and load analysis, which is very different from that of traditional rigid structures. In terms of structural optimization, Li, X. et al. [19] considered the contact interaction between the cable network and the membrane in air-supported membrane structures by designing a scale model and measuring the structural shapes and forces, established a contact model using ANSYS 19.0 software, and analyzed the effects of dif-

ferent contact states on the prestressing of the cable network. The study emphasizes the need to consider the effects of the sliding contact between the cables and the membrane in the design of the membrane structure. Dinh, T.D. et al. [20] considered the interaction of boundary cords with the tensioned membrane and optimized the shape of the tensioned cable-membrane structure with boundary cords so that the stress distribution of the structure achieves the target, and the difference between the designed shape and the obtained shape is minimized. Du, J. et al. [21] proposed a shape adjustment algorithm to reduce the discrepancy between the numerical simulation results and the actual shape for the problem of installation errors in the length of the cable network and the shape of the membrane. Shimoda, M. et al. [22] used the shape of the cable-membrane structure to minimize the membrane area and maximize the stiffness using his nonparametric optimization method based on the H1 gradient method. Cai, J. et al. [23] proposed a shape-finding optimization method based on the iterative correction of the tensioning process to optimize two evaluation indexes, namely, the mean square deviation of the membrane surface stress and the mean square deviation of the cable position of the structure. Zhao, H. et al. [24] used the NSGA-II algorithm for multi-objective optimization of the model in order to optimize the membrane surface stresses and the location of the cable network arrangement of the airship and determined the optimal solution through load analysis. In summary, the optimal design of cable-membrane structures needs to be mathematically modeled according to the judgment index of the structure and optimized by the optimization algorithm.

In a load analysis of air-supported membrane structures with emphasis on wind load response studies, Chen, Z. et al. [25] investigated the wind response and wind-resistant design method of spherical air-supported membrane structures based on wind pressure data obtained from wind tunnel experiments, taking into account the span, sagittal-to-span ratio, internal pressure, wind speed, and other factors. Cheon, D. et al. [26] investigated the wind pressure coefficient of dome roof membrane coverings using wind tunnel tests. Chen, Z. et al. [27] investigated the displacement and strain response of a spherical inflatable membrane under wind loading using a digital imaging technique (DIC). Sun, F. et al. [28] proposed a modified projection method and its solution procedure for strongly coupled integral equations. These were applied in a two-dimensional fluid–structure interaction benchmark case and in the calculation of wind-induced fluid–structure interactions for three-dimensional flexible membrane structures. Chen, Z. et al. [29] investigated the effect of disturbances on rectangular-planed surface air-supported membrane structures under different parameters (span, internal pressure, cable spacing, wind speed, etc.) on the basis of wind tunnel tests and wind response analysis. Geng, P. et al. [30] used a multiple load combination model in the stress and deformation analysis of containers in industry to calculate the actual displacement size, ensuring more uniform strength of the structure. The existing literature usually ignores live loads when analyzing the loads on air-supported membrane structures and lacks load combination analysis based on engineering practice and design codes. Therefore, a reasonable combination of permanent loads, live loads, and external wind and snow loads must be verified according to current codes when analyzing the loads on air-bearing membrane coal sheds.

The review of the above related literature shows that most of the current designs for membrane structures are based on previous project experiences, which are used as the basis for selecting the values of structural parameters (coal shed dimensions, internal pressures, spacing and number of cords and nets, etc.) in order to formulate feasible solutions. Such programs cannot compare the advantages and disadvantages of various types of air-supported membrane coal shed structural form design programs horizontally. Therefore, this paper is committed to establishing a standardized program design process and an analysis and optimization system of air-supported membrane coal sheds, optimizing the structural parameters of coal sheds through the establishment of mathematical models and improving the load-bearing performance of air-supported membrane coal shed structures, thus ensuring the safety of the structure, extending the service life of the structure, and reducing the maintenance cost of the structure.

Meanwhile, with the rapid development of membrane structure analysis software such as ANSYS, Easy, 3D3S, and other software can be used to determine the shape analysis and load analysis of large-span air-supported membrane structures. However, since the structural optimization design generally establishes the objective function and constraints according to the engineering reality and adjusts the structural parameters through the optimization method in order to come up with the best design scheme, the above structural calculation software needs to be involved in the engineering calculations of the stiffness, stresses and displacements, etc. However, the optimization algorithms that can be provided by the existing structural calculation software are often limited, so this study embeds a self-programmed optimization algorithm into the structural calculation software in order to achieve the joint optimization of the structure.

In this paper, we will focus on the optimization of air-supported membrane coal sheds with cable network stiffening, based on the engineering evaluation criteria and constraints abstracted as a mathematical model. ANSYS and MATLAB are jointly used to determine the optimal values of the structural parameters. At the same time, in order to avoid safety accidents during the use of the air-supported membrane coal shed, we should design a reasonable combination of loads for calibration. Therefore, we focus on the consideration of the response of the air-supported membrane coal shed under the wind load, and the average wind pressure coefficient and wind vibration coefficient of the membrane surface were determined by FLUENT simulation. Therefore, the response of the air-supported membrane coal shed under the wind load is considered, the average wind pressure coefficient and wind vibration coefficient of the membrane surface are determined by FLUENT simulation, and the permanent load, internal pressure, live load, and external wind and snow load are combined to form a load combination condition for verification, which is of certain significance for the load analysis of the air-supported membrane coal shed structure.

2. Modeling of the Structure Optimization Problem

2.1. Optimization Framework

Conventional design methods for air-supported membrane coal sheds with cable net stiffening lack optimization in cable net structure, internal pressure, and dimensions, leading to uncertainties in design advantages, cable net stress distribution, and costs. The traditional approach of conducting load analysis after the initial design and calibration poses risks of increased structural costs, material aging, and safety hazards over time. To address this, optimizing the structure by selecting suitable variables like internal pressure and rope net characteristics is crucial for enhanced safety and cost-effectiveness in the long run.

The optimized design of the air-supported membrane structure not only makes the morphological scheme satisfy the load analysis. It also establishes the evaluation criteria of the structure's working performance and load performance in daily use according to the working characteristics of the air-supported membrane coal shed and engineering practice and improves the shape of the design stage according to the feedback of the structural stress distribution and displacement response, so that the structure can achieve the optimal structural design shape in the morphological analysis stage and be better verified by load analysis.

The traditional optimization idea requires load analysis and engineering verification of the structure at each iteration, whereas the load analysis of the air-bearing membrane coal shed requires fluid simulation to determine the displacement and stress distribution of the final structure and verification, which leads to excessive computation when the number of iteration steps is large.

Another solution is to apply a uniform load to the air-supported membrane structure, use the optimization algorithm to optimize and rank the structure, and then start from the optimal solution to check whether it passes. Then, the sub-optimal solution is checked until the solution meets the engineering standards, as shown in Figure 2. Comparing the two

ideas, it can be seen that the second idea does not need to analyze the structure under the load in each iteration, which can reduce the amount of computation. The optimal design of the air-supported membrane coal shed shape can determine the evaluation criteria, judge the advantages and disadvantages of the design scheme, and at the same time, use the optimization algorithm to adjust the parameters of the air-supported membrane coal shed structure through the value of the objective function of the structure and the feedback of the loaded response, so the optimization design process has been improved compared with the traditional design process of an air-supported membrane coal shed.

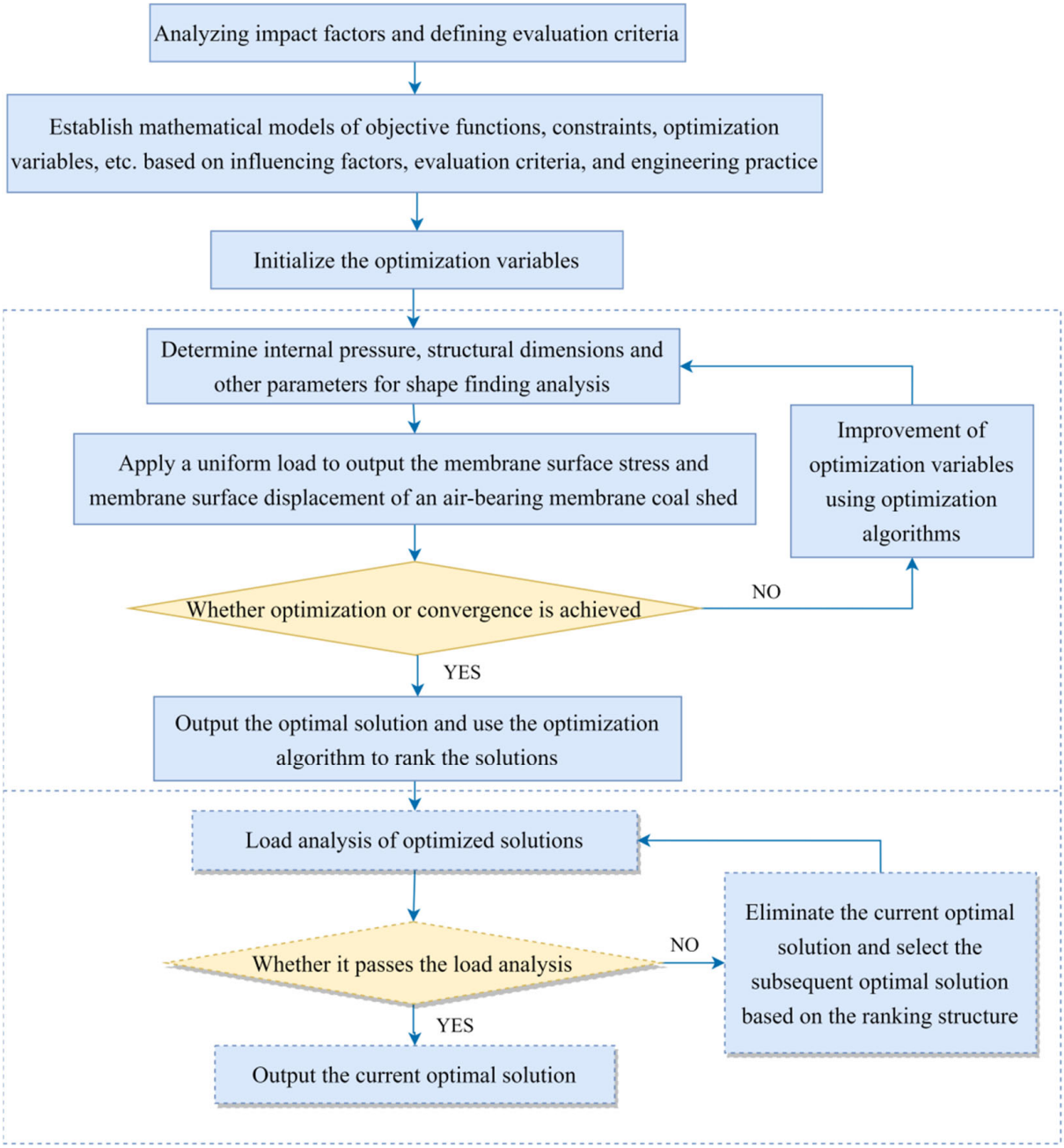


Figure 2. Optimization framework for air-supported membrane coal shed.

2.2. Objective Function

To optimize the morphological structure of the air-supported membrane coal shed, the optimization objectives can be designed as the optimal stress distribution on the membrane surface, the optimal ability of the structure to withstand external loads, and the

lowest cost of the structure, so the objective function is established for the optimization objectives below.

2.2.1. Membrane Surface Stress

In order to optimize the stress distribution on the membrane surface, it is necessary to minimize the maximum stress on the membrane surface and to have a more uniform stress distribution on the membrane surface [20]. After discretizing the structural finite element, the membrane surface is discretized into N triangular units, and each unit is subjected to different stresses. Let each unit be subjected to a stress of σ_i, where $(i = 1, 2, \cdots, N)$; then, the mathematical model to establish the criterion for judging the maximum membrane surface stress is as follows:

$$f_1 = min(MAX(\sigma_{\mathrm{i}})) \tag{1}$$

If the maximum stress on the membrane surface is smaller, it means that the membrane can also withstand larger external loads, and in order to avoid uneven stress on the membrane surface, the membrane surface stress distribution should be more uniform. This criterion can be used to judge the variance of the stress on each unit. If it follows that the more uniform the distribution of stress, the smaller the variance [23], then the variance can be obtained as follows:

$$D(\sigma_{\mathrm{i}}) = \frac{1}{N}\sum_{i=1}^{N}\left[\sigma_{\mathrm{i}} - E(\sigma_{\mathrm{i}})\right]^2 \tag{2}$$

$$E(\sigma_{\mathrm{i}}) = \frac{1}{N}\sum_{i=1}^{N}\sigma_{\mathrm{i}} \tag{3}$$

where $E(\sigma_{\mathrm{i}})$ denotes the expectation of the stress value of the membrane cell; $D(\sigma_{\mathrm{i}})$ is the stress value variance. The objective function is established as follows:

$$f_2 = min(D(\sigma_i)) \tag{4}$$

2.2.2. Coal Shed Loading

In the initial form of the design analysis, air-supported membrane structures can have a certain stiffness under internal pressure and resist external loads. Structural stiffness is generally reflected by the strain energy of the structure under the load. The smaller the strain energy, the greater the structural stiffness, but also can be used to characterize the size of the displacement of the structure after loading and the ability of the air-supported membrane coal shed to resist external loads [22]. The air-supported membrane structure is mainly subjected to self-weight, internal pressure, and external wind and snow loads, and the internal pressure has been considered in the shape-finding process. The self-weight and external wind and snow loads finally act on the membrane surface, which can be regarded as a vertically downward force. Therefore, in order to speed up the calculation speed in the iterative process, the self-weight and the wind and snow loads are considered as a vertically downward homogeneous load, and the displacement of each node on the membrane surface can be easily obtained due to the finite unitization of the air-bearing membrane coal framework under this load. Under this load, due to the finite unitization of the air-supported membrane coal framework, it is easy to obtain the displacement of each node on the membrane surface, so the total displacement after loading is used to express the structural rigidity, and if the total displacement is smaller, then the rigidity is greater, i.e., it has a stronger ability to resist external loads. Let the membrane surface be discretized into N nodes in the finite element analysis, the coordinate value of node i is $(x_{\mathrm{i}}, y_{\mathrm{i}}, z_{\mathrm{i}})$ after the shape-finding analysis, the coordinate of node i becomes $(x'_{\mathrm{i}}, y'_{\mathrm{i}}, z'_{\mathrm{i}})$ after the application of the load, and the displacement generated by the loading is $\left(u_{\mathrm{x}}, u_{\mathrm{y}}, u_z\right)$, which is satisfied as follows:

$$\begin{cases} u_{\mathrm{x}} = x'_{\mathrm{i}} - x_{\mathrm{i}} \\ u_{\mathrm{y}} = y'_{\mathrm{i}} - y_{\mathrm{i}} \\ u_z = z'_{\mathrm{i}} - z_{\mathrm{i}} \end{cases} \tag{5}$$

Therefore, the mathematical expression for the criterion of minimizing the total structural displacement is as follows:

$$f_3 = min\left(\sum_{i=1}^{N}\left(|u_x| + |u_y| + |u_z|\right)\right) \tag{6}$$

2.2.3. Cost of Construction

Let the price per unit area of membrane material be k_1, the price per unit volume of cable material be k_2, and the cost per unit volume of indoor inflation be k_3. Then, the overall investment cost of the structure can be expressed as follows:

$$Cost_z = Cost_m + Cost_s + Cost_q \tag{7}$$

$$Cost_m = k_1 \cdot \sum_{i=1}^{N} A_i \tag{8}$$

$$Cost_s = k_2 \cdot \sum_{i=1}^{N} \left(L_i A_{si}\right) \tag{9}$$

$$Cost_q = k_3 \cdot V \tag{10}$$

where $Cost_m$ is the cost of the membrane material; $Cost_s$ is the cost of the cable material; $Cost_q$ is the cost of air pressure; A_i is the unit area of the membrane unit i; L_i is the unit length of the cable unit i; A_{si} is the cross-sectional area of the cable unit i; and V is the volume of the air-bearing membrane coal shed.

For rectangular air-supported membrane coal sheds of different sizes, a larger span will result in a larger cost of the membrane surface, as well as a higher cost of the air pressure required to maintain it, and the cords and nets used on the surface may also be higher, but a larger span can provide more space for use. At the same time, under a fixed site, if the span is smaller, it will cause the site utilization rate to be insufficient. For the span, a smaller air-supported membrane coal shed must take into account the loss of space brought about by the lack of space, and the site utilization rate is not high, so this paper designs a penalty factor λ at this time to consider the cost of the span factor. The $Cost$ can be expressed as:

$$Cost = Cost_z - \lambda \times (200 - w) \tag{11}$$

Equation (11) indicates that a span of 200 m is the maximum span; if the span w is smaller, the $Cost$ is larger. Therefore, the cost evaluation criteria to establish a mathematical model is as follows:

$$f_4 = min(Cost) \tag{12}$$

From the above analysis, it can be seen that the optimization design problem of the air-supported membrane coal shed is a multi-objective optimization problem, and there are more criteria for judging the membrane surface, so it is necessary to deal with the objective function; otherwise, it will result in the design of the algorithm being very complex. In the above objective function, f_1, f_2, f_3 are based on the judgment of the loaded performance of the air-bearing membrane coal shed. f_4 is the air-bearing membrane coal shed cost optimization, so the above objective function can be processed into two objective functions: the first objective function for the synthesis of f_1, f_2, f_3 and the second objective function for f_4.

$$F_1 = \lambda_1 \times f_1 + \lambda_2 \times f_2 + \lambda_3 \times f_3 \tag{13}$$

$$F_2 = f_4 \tag{14}$$

Among them, F_1 characterizes the bearing capacity of the air-supported membrane coal shed: the smaller its value, the better the bearing capacity. $\lambda_1, \lambda_2, \lambda_3$ are the weights of the judging criteria f_1, f_2, f_3, and the sum of the three is 1. F_2 indicates the cost of the air-supported membrane coal shed: the smaller its value, the lower the cost. As for the

air-supported membrane structure, the maximum stress may be extremely large in the order of magnitude, the displacement value of each node is generally not more than 10 m, and the variance of the stress distribution is a value greater than 0 and less than 1. Therefore, there is a large gap between the results of the three calculations in the order of magnitude. As such, the three items of F_1 need to be relativized. Assuming that the maximum stress obtained in the first iteration is f_{11}, the variance of the stress distribution is f_{21}, and the displacement is f_{31}. After the ith iteration, the maximum stress obtained is f_{1i}, the variance of the stress distribution is f_{2i}, and the displacement is f_{3i}. At this point, the three terms of the relativization process are f_1', f_2', f_3', which can be expressed as follows:

$$f_1' = f_{1i}/f_{11} \tag{15}$$

$$f_2' = f_{2i}/f_{21} \tag{16}$$

$$f_3' = f_{3i}/f_{31} \tag{17}$$

Therefore, the final objective function can be expressed based on

$$minF_1 = \lambda_1 \times f_1' + \lambda_2 \times f_2' + \lambda_3 \times f_3' \tag{18}$$

$$minF_2 = f_4 \tag{19}$$

2.3. Optimization Variables

After defining the criteria for judging the advantages and disadvantages of the air-supported membrane coal shed design scheme as the objective function, it is necessary to analyze the factors that have an important influence on the objective function as the optimization variables and to adjust the optimization variables to make the structure better. Internal pressure, span, and sagittal height are important structural parameters that affect the loading performance of air-supported membrane coal sheds. The length often depends on the size of the construction site, so the design variables should include the internal pressure, span, and sagittal height. The number and spacing of cords and nets will affect the membrane surface morphology, and reasonable spacing and the number of cords and nets play an important role in the stress transfer and have a greater impact on the cost of the whole air-supported membrane structure [21]. If the spacing is too small, and the number is too large, it not only affects the structural cost, but also increases the construction difficulty; if the spacing is too large, it is difficult to stiffen the membrane surface. In the absence of cable network stiffening, the membrane surface tends to be in the center if the stress is greater. If the cable network is asymmetrically distributed, it will make the air membrane stress distribution uneven, and the membrane surface shape can not be controlled. Since the air-supported membrane coal shed studied in this paper is mainly a rectangular air-supported membrane, only the commonly used longitudinal and transversal cable net-stiffening methods and diagonal orthogonal cable net-stiffening methods are considered, and the cable net stiffening must be distributed symmetrically. Since the wire rope used in the cable net must be riveted to the surrounding foundations, the final distribution shape of the cable net can be determined by the shape of the cable net, the spacing of the cable net, and the riveting points of the cable net in the longitudinal and transverse directions. The form of cable network engineering is generally based on the structural span: if the span of the air-supported membrane coal shed structure is 90 m~120 m, a longitudinal and transverse cable network and oblique orthogonal cable network stiffening can be chosen; oblique orthogonal cable network stiffening mode load performance is better for a span of more than 120 m. In the structural optimization design problem, if we consider various factors, it will complicate the optimization problem, so this paper expresses the design variables as follows:

$$X = (w, h, l_1, l_2, n_1, n_2, P) \tag{20}$$

where w is the span; h is the sagittal height, which affects the loaded performance of the final structure; l_1, l_2 denote the spacing of the cords in the length direction and span direction, respectively; n_1, n_2 denote the number of cords in the length direction and span direction, respectively, which affects the stress distribution of the membrane surface; and P is the working internal pressure, which affects the stress distribution of the final membrane surface and the maximum displacement of the membrane surface.

2.4. Constraints

The optimization design problem of the air-supported membrane coal shed needs to satisfy certain performance constraints and geometric constraints according to the engineering reality. The main performance constraints are as follows:

(1) No tearing of the membrane material and no fracture of the cable network. The membrane material does not tear, and the cable network does not break. According to the thickness of the diaphragm material and the safety factor, the maximum tensile force that the diaphragm material can withstand and the minimum tensile force that should be maintained can be calculated. From these values, the diaphragm material stress limit can be obtained. The maximum tensile force that can be withstood by the rope net can be calculated according to the cross-sectional area and material parameters. The constraint is then expressed as follows:

$$\sigma^{\mathrm{F}}_{\mathrm{min}} \leq \sigma_{\mathrm{i}} \leq \sigma^{\mathrm{F}}_{\mathrm{max}} \tag{21}$$

$$\sigma^{\mathrm{F}}_{\mathrm{smin}} \leq \sigma_{\mathrm{si}} \leq \sigma^{\mathrm{F}}_{\mathrm{smax}} \tag{22}$$

(2) Node displacement constraints. Based on the nonlinear finite element method, the membrane surface and the cable surface are discretized into units and nodes, and the nodes shared by the units should have the same x, y, and z direction displacements. The node displacements should be less than their maximum values. For the whole structure, the displacements of membrane units and cable units should have an upper and a lower boundary [31]. The constraints are expressed as follows:

$$d_{\mathrm{k}} \leq d_{\mathrm{max}} \tag{23}$$

(3) No folds appear in the process of shape finding. When the membrane unit in a certain direction of the tensile stress disappears, the membrane cannot bear pressure, and thus wrinkles appear. The generation of folds will make the structural load-bearing capacity decline, so the shape analysis needs to consider the problem of membrane folds. The relaxation and folding of the membrane surface can be judged by the value of the principal stress of the membrane unit. If both the maximum stress σ_{max} and the minimum stress σ_{min} of the membrane unit are greater than 0, the membrane unit is functioning normally; if both are less than 0, then it cannot function properly; if σ_{max} is greater than 0 and σ_{min} is less than 0, the membrane assembly is stretched and cannot function properly. Therefore, in the process of shape finding, the size of the internal pressure or the stress distribution of the membrane surface should be adjusted to avoid the occurrence of the second and third situations. The relaxation of the cable network can be judged based on whether the cable axial stress is positive or not. The constraints are as follows:

$$\sigma_{\mathrm{max}} \geq \sigma_{\mathrm{min}} > 0 \tag{24}$$

The main geometric constraints are as follows:

(1) Length, span, and vector height constraints

The length of the air-supported membrane coal bin is connected by the membrane belt, which has nothing to do with the width of the membrane belt in the force analysis. Therefore, the length mainly depends on the size of the site in the actual engineering design, and the length and span of the air-bearing membrane coal shed should be smaller than the length and span of the site. For the value of the vector height, according to the engineering design specifications, the vector span ratio of the air-bearing membrane structure should

be not less than 1/3 and not more than 2/3 [31]. For no snow load or a snow load that is not large and the installation of a snow removal and melting device in the air-bearing membrane coal shed, the vector span ratio can be between 1/6 and 2/3 [31]. The sagittal height of the air-bearing membrane coal shed should be greater than the height of the internal equipment. Due to the deformation of the structure when subjected to external loads, the surface of the air membrane and the internal equipment should be spaced apart. The specific constraints are met as follows:

$$0 \le a \le a_{\max} \tag{25}$$

$$0 \le w \le w_{\max} \tag{26}$$

$$P_{\min} \le P \le P_{\max} \tag{27}$$

$$h_{\min} \le h \le h_{\max} \tag{28}$$

$$\frac{1}{6} \le \frac{h}{w} \le \frac{2}{3} \tag{29}$$

(2) Number and spacing constraints for cable nets

When arranging the rope net, the number, spacing, and diameter of the rope net will affect the coverage of the rope net, which should not be larger than the area of the membrane. At the same time, it should be ensured that the riveting points of the rope net can be reserved in the longitudinal direction and the span direction of the air-supported membrane coal shed, so it is assumed that the rope net adopts the longitudinal and transverse rope net. The length of the air-supported membrane coal shed is a, the number of the rope net in the longitudinal direction is n_1, and the spacing is l_1; the span is w, the number of the rope net in the span direction is n_2, and the spacing is l_2. This should be satisfied as follows:

$$a \ge (n_1 - 1) \times l_1 \tag{30}$$

$$w \ge (n_2 - 1) \times l_2 \tag{31}$$

2.5. Mathematical Model for Optimal Design of Air-Supported Membrane Coal Shed

Based on the above finite element analysis of the structure, the mathematical model of the optimization design problem of the air-supported membrane coal bin is established, which mainly includes optimization variables, objective functions, and constraints.

The optimization variables are as follows:

$$X = (w, h, l, n, P) \tag{32}$$

The objective function is as follows:

$$\begin{cases} minF_1 = \lambda_1 \times f_1' + \lambda_2 \times f_2' + \lambda_3 \times f_3' \\ minF_2 = f_4 \end{cases} \tag{33}$$

The model constraints are as follows:

$$\sigma_{\min}^{\mathrm{F}} \le \sigma_{\mathrm{i}} \le \sigma_{\max}^{\mathrm{F}} \tag{34}$$

$$\sigma_{\mathrm{smin}}^{\mathrm{F}} \le \sigma_{\mathrm{si}} \le \sigma_{\mathrm{smax}}^{\mathrm{F}} \tag{35}$$

$$d_{\mathrm{k}} \le d_{\max} \tag{36}$$

$$\sigma_{\max} \ge \sigma_{\min} > 0 \tag{37}$$

$$0 \le a \le a_{\max} \tag{38}$$

$$0 \le w \le w_{\max} \tag{39}$$

$$P_{\min} \le P \le P_{\max} \tag{40}$$

$$h_{\min} \leq h \leq h_{\max} \tag{41}$$

$$\frac{1}{6} \leq \frac{h}{w} \leq \frac{2}{3} \tag{42}$$

$$\mathrm{a} \geq (n_1 - 1) \times l_1 \tag{43}$$

$$\mathrm{w} \geq (n_2 - 1) \times l_2 \tag{44}$$

Among them, Equations (34) and (35) indicate that the stresses of the membrane material and the rope material after loading should not exceed the permissible value, and at the same time, they should not be lower than the minimum stress requirement, respectively. Equation (36) indicates that the displacement of each node should not be higher than the maximum permissible displacement. Equation (37) indicates that there is no wrinkle in the structure of the air-supported membrane-type coal scaffold. Equations (38)–(44) indicate that the length, span, internal pressure, sagittal height, sagittal-to-span ratio, and interval of the cords should be within a reasonable range. Equations (43) and (44) indicate that the interval, number, and size of the cords should be within a reasonable range.

3. Methods

3.1. ANSYS and MATLAB Joint Optimization

In this paper, with the help of the APDL module of ANSYS software, the self-programmed program based on the finite unit method can easily calculate the stress distribution and displacement of the structure, and the establishment of constraints is also relatively simple. Through the scalability of the parametric design language (APDL), it can be parameterized to the design variables, and its batch operation can be completed in the background of the finite element analysis to improve the efficiency of the work based on the basis of ensuring the accuracy of the calculations. The work efficiency is improved on the basis of ensuring the computational accuracy. Based on the aforementioned mathematical model and structural nonlinear finite element analysis, the optimization algorithm is used to realize the optimization design process of the air-supported membrane coal shed as shown in Figure 3.

For the optimization design problem of the air-supported membrane coal shed, in this paper, the objective functions such as membrane surface stress and structural displacement cannot be directly expressed by design variables, and it is not easy to establish accurate mathematical models of constraints and design variables. Due to the large number of optimization objectives in this paper and the fact that the APDL language does not have the advantage of algorithm programming, it is more difficult to complete all the optimization design work using only APDL. It is easier to program the optimization algorithm in MATLAB. Combining the respective advantages of ANSYS and MATLAB, this paper develops "ANSYS-APDL Batch Processing" through the main program of MATLAB and writes the optimization algorithm in MATLAB, then uses ANSYS to analyze the morphology of the air-bearing coal shed with the stiffening cable network. The optimization algorithm is written in MATLAB, and ANSYS is used to analyze the morphology of the air-supported coal shed with the stiffening cable network. Data transfer between the software is used to complete the automation of the iterative operation, and the optimization calculation is carried out by the improved intelligent algorithm in MATLAB to search for the optimal solution. This leads the objective function of the optimization of the air-supported coal shed to achieve the maximum value, and thus the optimization of the structures is achieved. The flow of the optimization method of the joint design of the air-bearing coal shed in MATLAB and ANSYS is shown in Figure 4.

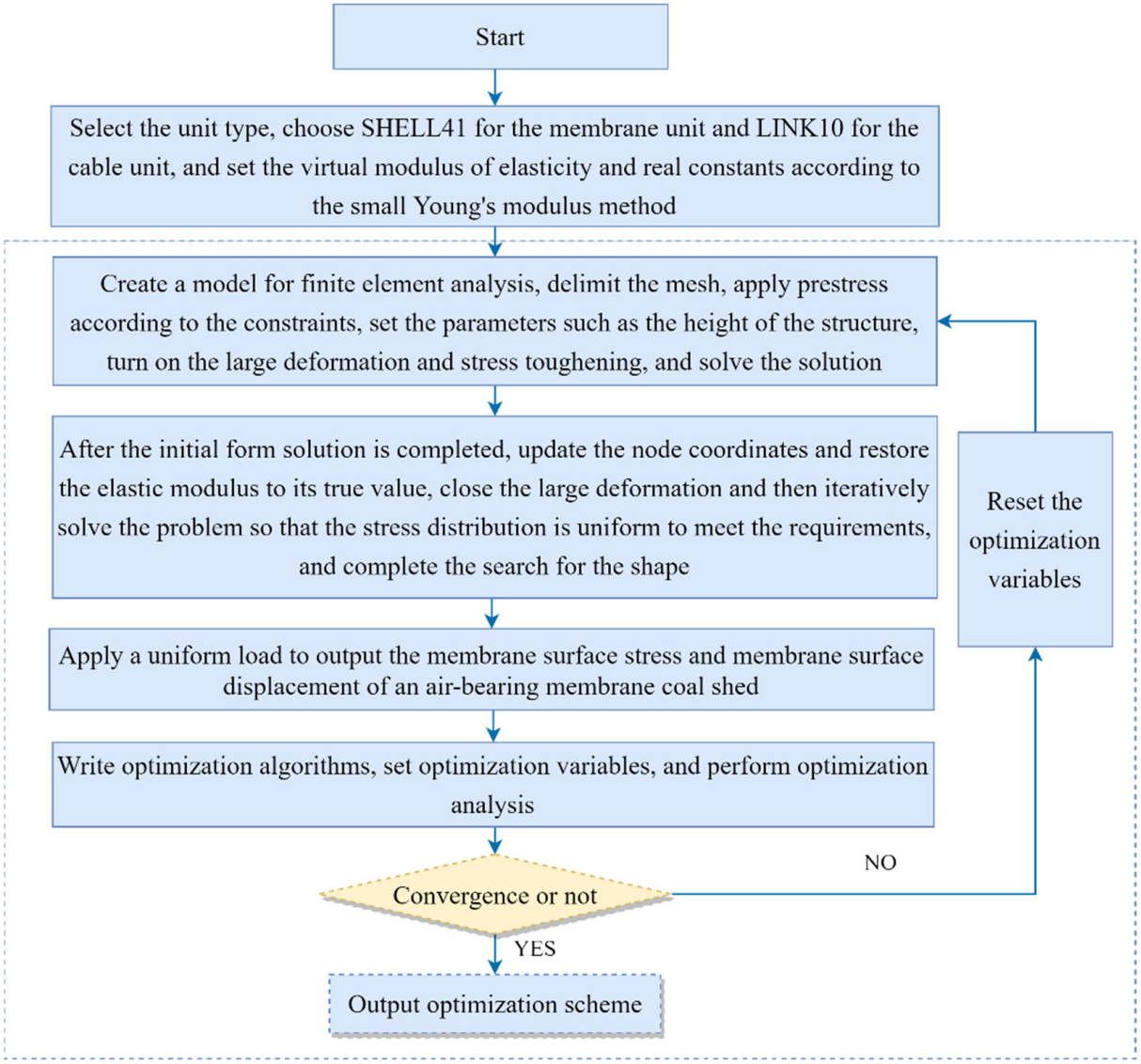


Figure 3. Optimization process of gas film coal shed structure.

3.2. Improved NSGA-II Optimization

The optimization problem of the air-supported membrane coal shed structure is a multi-objective optimization problem. It is not easy to directly write the explicit expression between the optimization variables and the objective function and constraints, and it is not possible to solve it mathematically, so in this paper, we use MATLAB to write heuristic algorithms for optimization [24]. As the final optimization model of the air-supported membrane coal shed established in this paper is a bi-objective problem, there are four criteria for judging the advantages and disadvantages of the air-supported membrane coal shed. The values of the optimization variables tend to mean that one objective is better and the other worse, so it is difficult to make all the objective functions remain optimal at the same time. Therefore, the optimization algorithm in the iterative search for the optimum can only ensure that part of the objective function is optimized, and at the same time, that the other objective function does not deteriorate. Therefore, the iterative optimization algorithm can only ensure that some of the objective functions are optimized, and others are not degraded. The solution set obtained from optimization is the Pareto optimal solution. In order to solve the Pareto optimal solution for the optimal design of the air-supported membrane coal shed structure, this paper improves the NSGA-II algorithm by using MATLAB programming and embedding it into the structural analysis of ANSYS

as the optimization algorithm for the optimal design of the gas-bearing membrane coal shed. The specific algorithmic design process and improvement method are as follows:

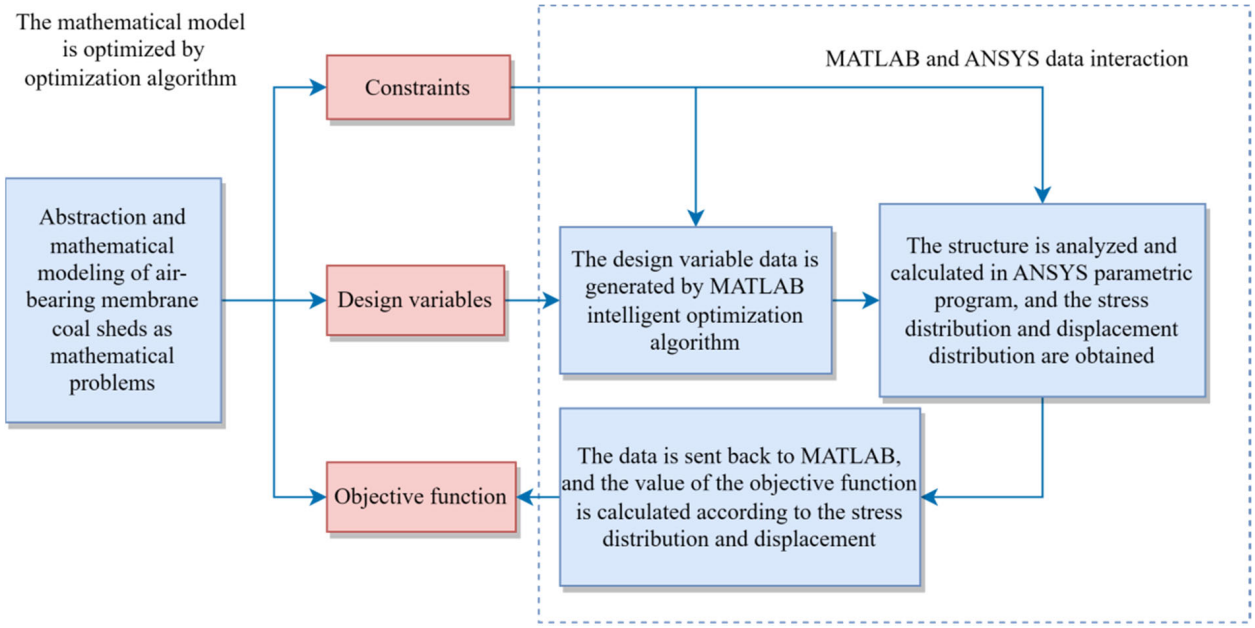


Figure 4. Flow chart of gas-bearing film coal shed optimized by MATLAB and ANSYS.

(1) Chromosome coding and decoding

The NSGA-II algorithm regards each design scheme as a chromosome and constantly seeks optimization through crossover, mutation, and selection between chromosomes, so the first step of the algorithm is to encode and decode the chromosomes of the individuals in the population. Because binary coding has better anti-interference and programming is easier to realize, this paper uses binary coding. According to the actual engineering settings of each optimization variable range, the precision and the number of binary bits required are shown in Table 1. Examples of encoding and decoding methods are shown in Figure 5.

Table 1. Optimized variable range and binary representation accuracy and bits.

	Radius	Precision	Desired Bits
Structural span	120 m–200 m	1 m	7
Structural vector height	50 m–80 m	1 m	5
Reference internal pressure	100 Pa–300 Pa	10	5
Cable spacing	2 m–7 m	0.1 m	6
Cable quantity	0–100	1	7

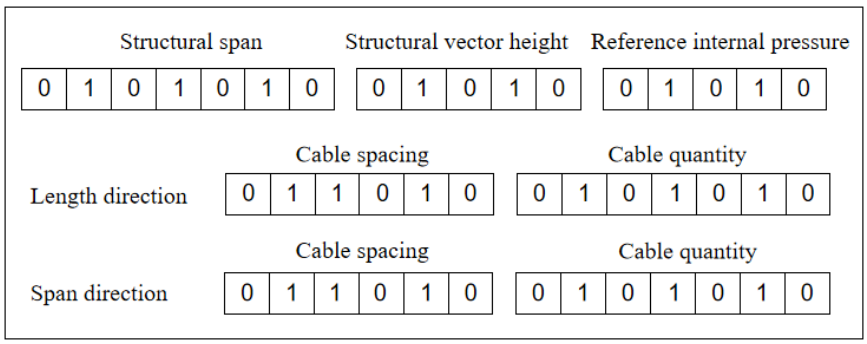


Figure 5. Encoding example.

The decoding method first converts the above binary to a decimal, then multiplies it with the precision and adds the minimum value of the optimized variable range. Therefore, the above coding example shows that the program is as follows: the air-supported membrane coal shed span is 162 m, the structural vector height is 60 m, the base internal pressure is 200 Pa; the length direction of the cable network interval is 4.6 m, and the number of the cable network is 42; the span direction of the cable network interval is 4.6 m, and the number of the cable network is 42.

(2) Calculation of adaptation values

The NSGA-II algorithm for non-dominated sorting and selection of individuals needs to be based on the degree of individual superiority or inferiority that is the size of the fitness value for judgment. The design of the fitness function needs to be determined according to the objective function. In this paper, the value of the objective function are non-negative, and all to minimize the optimal, so take the inverse method and the introduction of coefficients to prevent the fitness value is too small or too large and not easy to compare, the method is as follows:

$$S_i = b_i \frac{1}{F_i} \tag{45}$$

Since the number of objective functions in this paper is 2, i is taken as 1 or 2. For F_1, since the final optimized solution keeps converging and its value decreases from around 1, the objective function value is enlarged by 100 times in the fitness value calculation, i.e., b_1 is taken to be 100. For F_2, since it indicates the cost, its value is larger, and the objective function value is reduced by 10,000 times in the fitness value calculation, i.e., b_2 is taken to be 1/10,000.

(3) Elite strategies and ways to improve them

The traditional NSGA-II algorithm generally adopts the elite retention strategy for individual screening, so this paper improves the original elite retention strategy by setting the parameter α, changing the original N individuals that should be directly retained to only retain the first $N \times \alpha$ individuals to join the new population. Meanwhile, the first $N \times (1 - \alpha)$ individuals are selected from the N individuals that should have been eliminated. The process is shown in Figure 6. Mixing the retention of elite and eliminated individuals can prevent the loss of the obtained Pareto optimal solution to a certain extent, but also retain the excellent genes in the eliminated individuals, preventing the algorithm from converging quickly or falling into local optimal solutions.

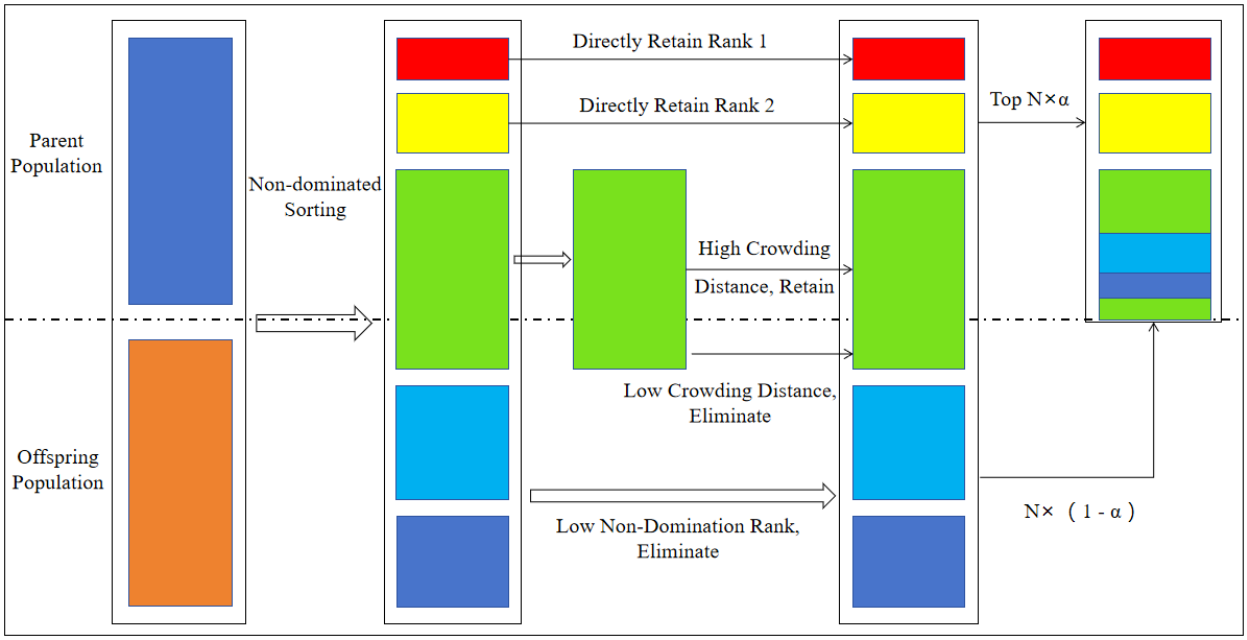
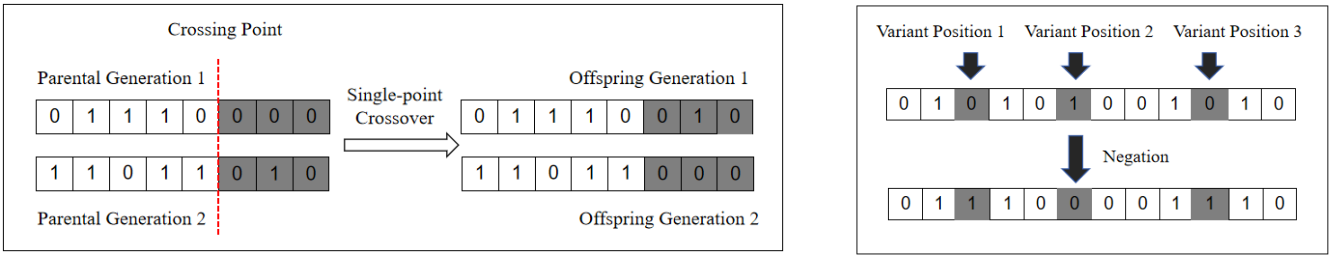


Figure 6. Improving the elite strategy selection method.

(4) Crossover, mutation operations

The NSGA-II algorithm needs to obtain new population individuals to keep iterating to find the optimal, and the ways to generate new individuals are crossover and mutation. Since this paper uses binary coding, in order to avoid damage to the better chromosomes, the individual mating method is selected as single-point crossover, and the operation is shown in Figure 7a.



(**a**) Schematic diagram of a single-point crossing (**b**) Schematic diagram of multi-point variation

Figure 7. Crossover and mutation operations.

The mutation operation will output new gene segments, which is conducive to enriching population diversity, while keeping the algorithm from falling into local optimal solutions. In this paper, we adopt a multi-point mutation strategy for binary coding. The mutation operation is an inverse operation, and the operation is shown in Figure 7b.

3.3. Joint Optimization Algorithm Flow

The NSGA-II algorithm based on MATLAB is embedded in ANSYS to carry out structural optimization calculations, and its optimization process is shown in Figure 8. The specific steps are as follows: (1) set the parameters of the NSGA-II algorithm in MATLAB, and initialize the population; (2) decode the current population using MATLAB, and generate the input file. ANSYS reads the file to give the values of the structural parameters, and ANSYS reads in the file to assign values to the structural parameters and calculates them to obtain the membrane surface stress and structural displacement; (3) ANSYS outputs the output file, and MATLAB reads in the file to obtain the membrane surface stress and structural displacement and calculates the value of the objective function; (4) calculate the fitness of the population according to the value of the objective function, and perform the calculation of its non-dominated sorting and crowding; (5) perform the operations of selecting, crossover, and mutation to generate the offspring populations, and then perform the merging; (6) calculate the fitness of the offspring population, and then calculate it compared with the parent population fitness; perform non-dominated sorting and congestion calculation together with the parent population; and generate a new population based on the improved elite retention strategy; (7) judge whether the termination criterion is satisfied, and terminate if it is satisfied; generate the Pareto solution set, and decode it to obtain multiple better design solutions; if not satisfied, repeat steps 2 to 6.

The essence of the joint optimization of MATLAB and ANSYS is based on the Batch mode of ANSYS, using MATLAB to write the optimization algorithm, and calling ANSYS in Batch mode to run APDL for structural calculations in order to obtain the fitness value required by the optimization algorithm and ultimately obtain the optimal solution. To call the APDL module for calculation under MATLAB, we only need to utilize the "system" command of MATLAB and the "Command Line" in Batch mode.

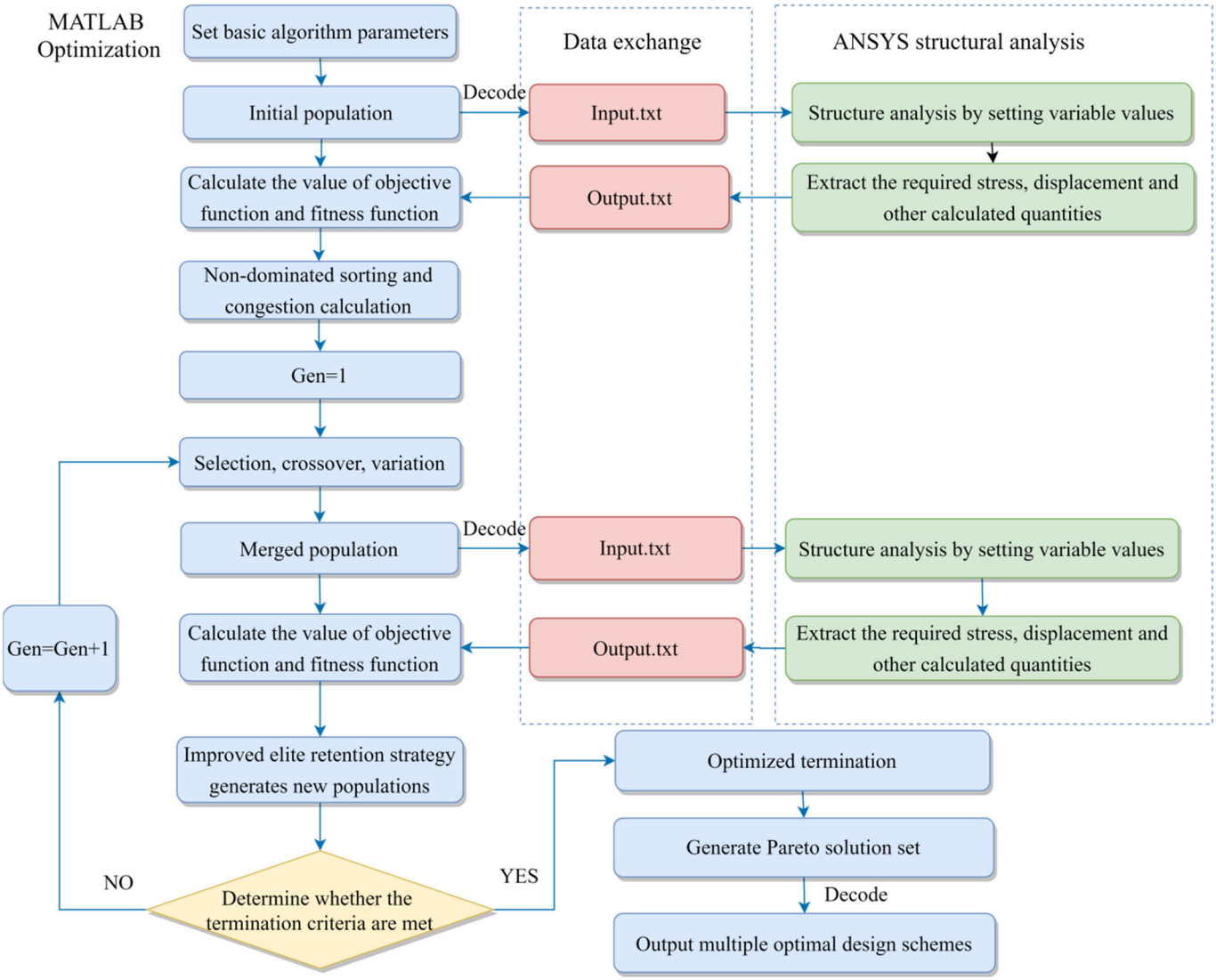


Figure 8. Flowchart of structural optimization with embedded ANSYS based on NSGA-II.

4. Case Study

4.1. Introduction to the Case

Based on the project cooperation with a gas-bearing membrane design enterprise, a power plant needs to close the original open coal storage yard. According to the requirements of the construction of the air-bearing membrane coal shed, the span should be between 190 m and 200 m, the length 225 m, and the height not less than 60 m due to the large span. According to the cable network design experience using a diagonal orthogonal cable network on the air-bearing membrane coal shed stiffening treatment, the shape of the completion of the application of the self-weight and the homogeneous load is found to be 0.3 kN/m^2. The material parameters of the cable network and membrane material are shown in Table 2.

Table 2. Structural parameters of film and cable material of gas-bearing film-type coal shed.

Material	Material Properties	Unit	Parameters
Film material	Thickness	mm	1.05
	Weight	kg/m^2	1.5
	Standard value of tensile strength	KN/cm	Longitude 37,500, latitude 35,000
	Modulus of elasticity	MPa	898
	Poisson's ratio	-	0.25
Cable material	Nominal diameter of cable	mm	20
	Weight	kg/m	16,700
	Minimum breaking force	KN	279

According to the above parameters and engineering practice, joint optimization of ANSYS19.0 and MATLAB2016a is used to select the internal pressure, cable network stiffening parameters, and span and vector height parameters of the above air-bearing membrane coal shed to optimize the load-bearing performance and cost of the air-supported membrane structure. The improved NSGA-II algorithm is written using MATLAB, and the model and algorithm parameters are shown in Table 3.

Table 3. Parameters of the model and optimization algorithm.

Parameters of the NSGA-II Algorithm Were Improved	Numerical Value
Population size	50
Genetic algebra	200
Initial crossover probability	0.9
Initial mutation probability	0.01
α	0.01
Penalty factor	100,000
Wire rope cost	10 yuan/m
Film cost	200 $yuan/m^2$
Inflation cost	10 $yuan/m^3$

4.2. Validation of Example Results

Using ANSYS to find the shape of the air-supported membrane coal shed and applying uniform load analysis, the maximum stress on the membrane surface, the displacement of each node, and the membrane area and cable length can be determined, and this is used to determine the cost required to maintain the shape of the air-supported membrane coal shed. Using the improved NSGA-II algorithm can produce different Pareto solution sets. Different solutions of the same level of solution set cannot be judged to be superior or inferior, so different schemes can be compared, and at the same time, in the same level of different schemes, the decision can also be based on the actual choice of the project. For the optimal design of the air-supported membrane coal shed, since the optimal level of the solution may not necessarily pass the later load analysis, if the first level of the solution cannot be passed, it can be determined be one-by-one in the next level of the engineering calibration to avoid the problem of relying on human experience only for the value of the engineering parameters.

Figure 9 illustrates the set of Pareto frontier solutions for the air-supported membrane coal shed optimization design problem generated using the improved NSGA-II algorithm. In a multi-objective optimization problem, the Pareto frontier is the set that represents all non-dominated solutions (i.e., solutions that cannot improve the value of at least one objective function without compromising the value of another objective function). The solution near the intersection of the red line with the Pareto frontier in the figure represents a better balance of both cost (F2) and structural performance (F1) objectives. The solutions

near the intersection of the remaining two lines with the Pareto front denote the set of solutions that has achieved a better value on a single objective, respectively. The decision maker can choose the most appropriate solution from the Pareto front according to the actual needs and budget constraints of the project.

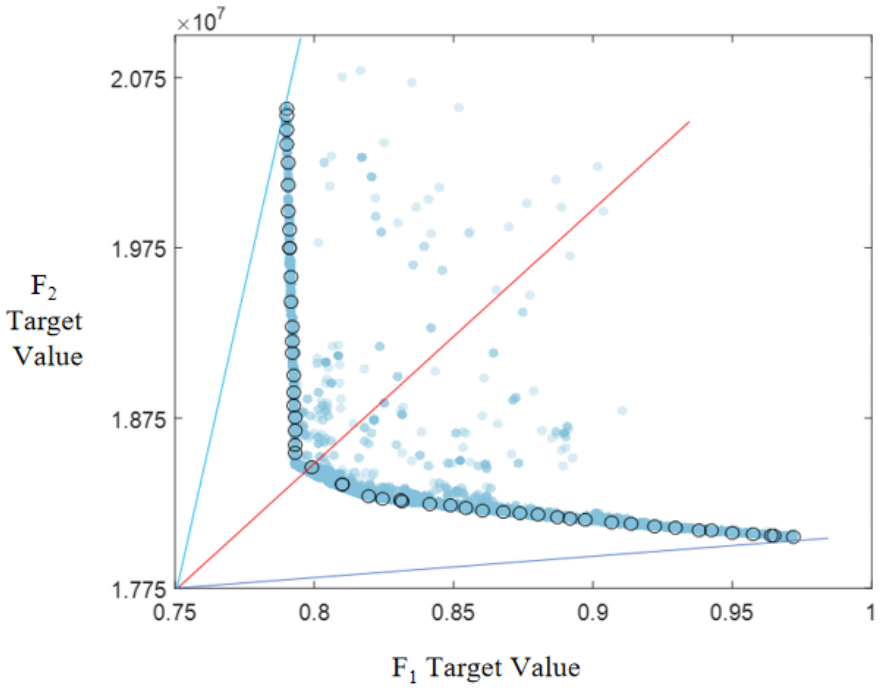


Figure 9. Pareto frontier solution.

Table 4 details the specific parameters of some of the Pareto front solution sets, including structural spans, heights, internal pressures, web spacing, number of webs, and the corresponding values of the two objective functions. The weights of F_1 and F_2 in this analysis are set to 1:1, i.e., the two objectives are equally important. For the sub-items in F_1, the weights are set to 0.4, 0.2, and 0.4, respectively, i.e., the weights of the objectives of minimum maximum stress and maximum stiffness are the same and are high, and the weights of the degree of uniformity of stress distribution are low. Due to the large span of the air-supported membrane coal shed, this weight setting pays more attention to the structural safety and prevents the membrane surface from tearing or structural collapse due to excessive stress or low stiffness.

Table 4. Part of Pareto frontier solutions.

	Optimal Solution 1	**Optimal Solution 2**	**Optimal Solution 3**
Structural span	195 m	198 m	190 m
Structural vector height	65 m	67 m	60 m
Structural internal pressure	280 Pa	260 Pa	290 Pa
Cable spacing l_1	2.0 m	3.5 m	2.1 m
Cable spacing l_2	2.0 m	2.3 m	2.0 m
Cable quantity n_1	100	61	100
Cable quantity n_2	95	75	95
F_1	0.81	0.84	0.78
F_2	18.30 million yuan	18.05 million yuan	18.76 million yuan

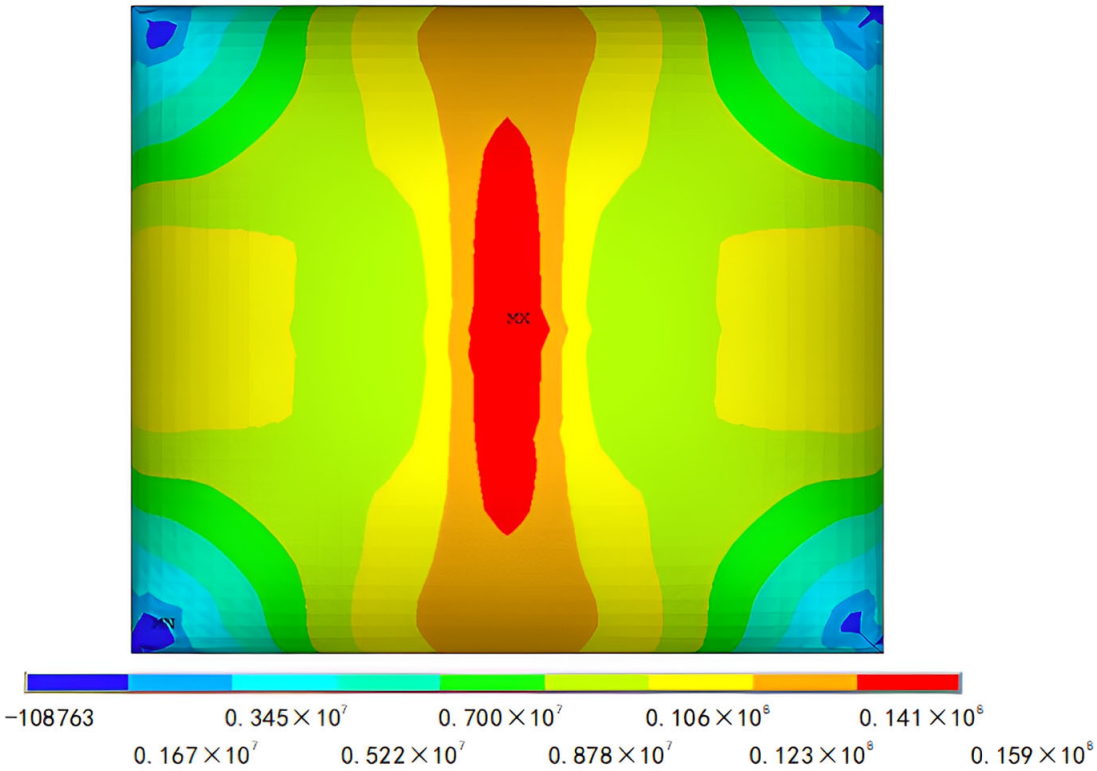
In this paper, the two objective functions are considered comprehensively. The above optimization solution 1 is finally selected as the final solution, and the final structural design parameters of the air-bearing membrane coal shed are as follows: span 195 m, height 65 m, length 225 m. Due to the larger span, the spacing of the cable network in the direction of the length and the span is 2.0 m at this time, and the structural sagittal-to-span ratio is 1/3, with a baseline internal pressure of 280 Pa. Comparing this solution with a certain solution generated from the initial population, the results of the loaded performance and cost comparison under the two solutions are shown in Table 5. The results of the comparison of the loaded performance and cost of the air-supported membrane coal shed under the two programs are shown in Table 5.

Table 5. Comparison of optimization results with initial scheme parameters and results.

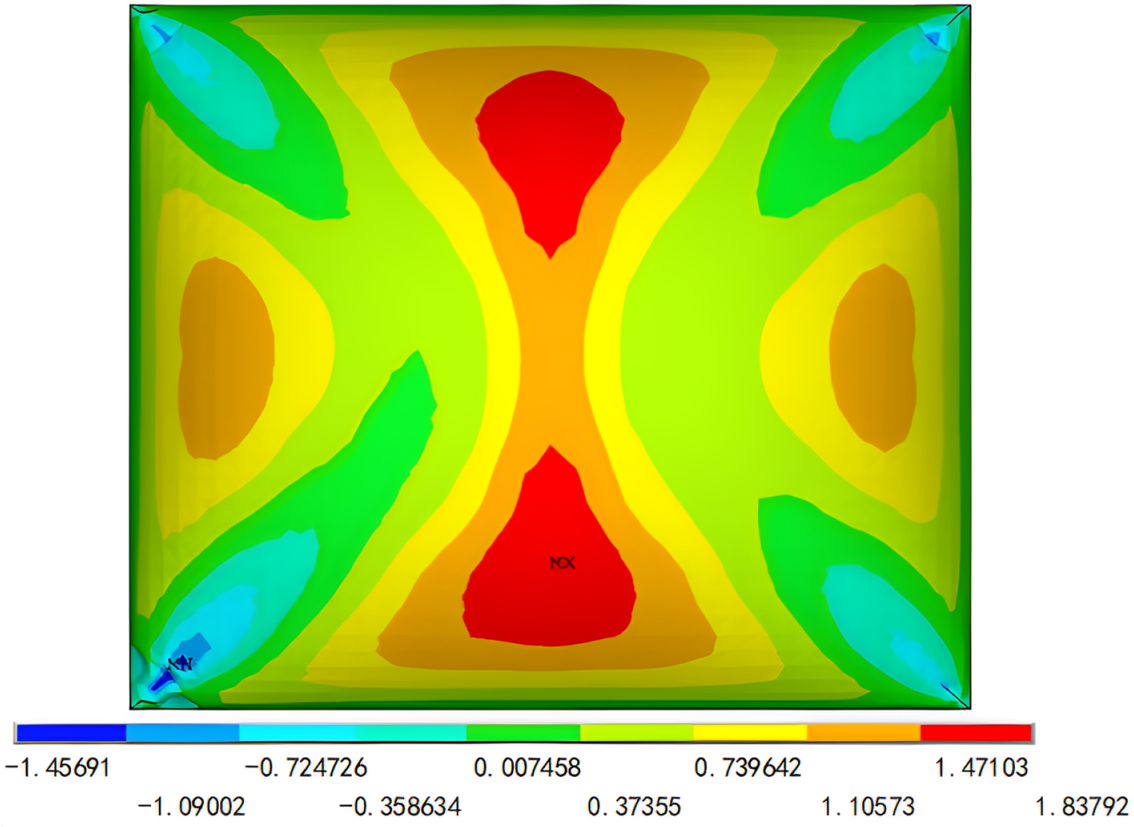
Structural Optimization Variable	Initial Scheme	Optimization Results of the NSGA-II Were Improved
Structural span	190 m	195 m
Structural vector height	70 m	65 m
Structural internal pressure	300 Pa	280 Pa
Cable spacing l_1	2.5 m	2.0 m
Cable spacing l_2	3.4 m	2.0 m
Cable quantity n_1	75	100
Cable quantity n_2	30	95
Maximum stress on the loaded film surface	16.8 MPa	15.9 MPa
Maximum displacement under load	2.64 m	1.84 m
Cost	RMB 20.3 million	RMB 18.3 million

Table 5 compares the performance of the initial design scheme with that of the design scheme optimized by the NSGA-II algorithm based on several key parameters. It can be seen that the optimized scheme has achieved significant improvements in several aspects. For example, the span of the optimized structure is increased from 190 m to 195 m, the height is reduced from 70 m to 65 m, and the internal pressure is reduced from 300 Pa to 280 Pa. These changes not only increase the volume of the coal shed, but also further improve the stability and safety of the structure by optimizing the configuration of the cords and nets (e.g., reducing the spacing of the cords and net and increasing the number of cords and nets). In addition, the optimized solution reduced both the maximum stress and maximum displacement at the membrane surface by 5.36% and 30.3%, respectively, and the cost was also significantly reduced from RMB 20.3 million to RMB 18.3 million. These improvements show that combining the respective advantages of the two software programs, MATLAB and ANSYS, and designing the improved NSGA-II algorithm to optimize and solve the above mathematical model is to a certain extent superior to using a single-solution software program. This method can find a more optimal solution and effectively improve the efficiency and economy of the design of the air-supported membrane coal shed.

The optimal solution obtained by the improved NSGA-II algorithm is verified by finite element analysis, and the stress maps of the membrane surface under self-weight, internal pressure, and a given uniform load are shown in Figure 10a. This figure shows that the maximum stress of the membrane surface still occurs at the top of the membrane surface. For the air-supported membrane structure, the maximum displacement is the z-direction displacement, and its displacement map is shown in Figure 10b. The maximum displacement occurs at the top two sides, and the displacement change distribution is more symmetrical.



(**a**) Stress contour map of the loaded membrane surface/MPa



(**b**) Displacement contour map in the z-direction/m

Figure 10. Optimization results of the numerical example.

From the figure, it can be seen that the optimized configuration of the cords and nets (e.g., using smaller cord and net spacing and more cords and nets) effectively improves the stress distribution state of the membrane surface. The stress concentration phenomenon is obviously reduced, and the overall stress level of the membrane surface is more uniform, which is of great significance for improving the structural safety and durability of the air-supported membrane coal shed. In addition, the fine design of the cable network can further optimize the efficiency of material use and reduce the construction cost while ensuring the structural stability.

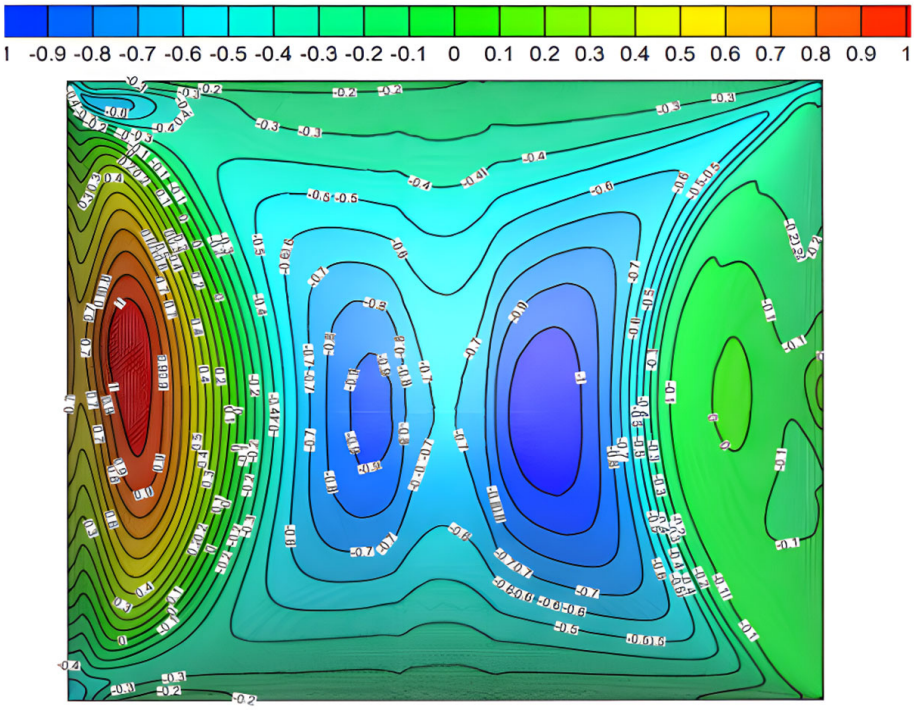
The above completes the structural optimization design of the air-supported membrane coal shed structure under a uniform load, and the optimization scheme can ensure that the air-supported membrane coal shed has better loading performance and more efficient cost in daily service. However, when actually put into use in the project, the influence of the coal shed structure under wind loads should also be taken into account. Here, we mainly analyze the effect of different wind angles on the pressure distribution of the membrane surface of the air-supported membrane coal shed. Through the establishment of the model fluid domain and the setting of FLUENT, we can calculate the surface wind pressure of each node on the air-supported membrane coal shed and the wind pressure coefficients of each measurement point. Then, we can make the contour plots of the wind pressure coefficients in CFD post-processing software, taking the 0-degree wind angle and the 60-degree wind angles as examples. The wind pressure coefficient contour plots are shown in Figure 11 below.

Secondly, the load combination of the air-supported membrane coal shed is checked and calculated. Using the limit state design method, the load combination is carried out with the expression of itemized coefficient design. It is verified that the strength and structural deformation of the air-bearing membrane coal shed structure under the load combination are in accordance with the engineering design value, and the load combination designed in this paper is as follows (as shown in Table 6): G is the structural weight of the air-bearing membrane coal shed structure, W is the wind load, Q is the larger value of the snow load versus the live load, Pmax is the maximum working internal pressure.

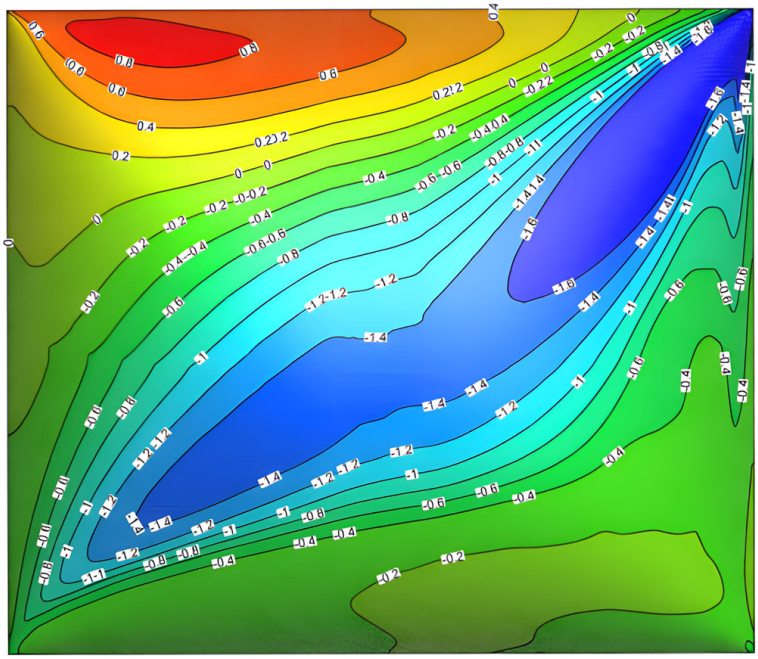
Table 6. Load combination table.

	Load Combination Sequence Number	Load Combination
Strength checking	1	$0.9G + 1.3P_{max}$
	2	$0.9G + 1.5W + 1.0P_{max}$
	3	$0.9G + 1.5W + 0.7 * 1.5Q + 1.0P_{max}$

Based on the optimization scheme obtained from the above analysis and solution, the air-supported membrane coal shed structure was analyzed to find the shape, and then the corresponding internal pressure was applied according to the load combination conditions. The results are shown in Figure 12 below. After the structure is stabilized, the self-weight load is applied, and then the external load is applied according to the load combination conditions. This load is applied to the surface of the air-supported membrane coal shed in the form of pressure, and the different load combinations are compared and analyzed.



(**a**) 0-degree wind angle.



(**b**) 60-degree wind angle

Figure 11. Contour map of corneal wind pressure coefficient at 15° wind direction and 60° wind direction.

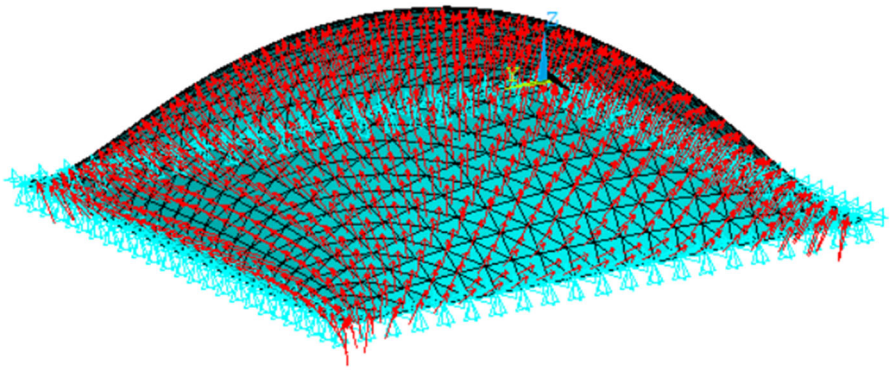
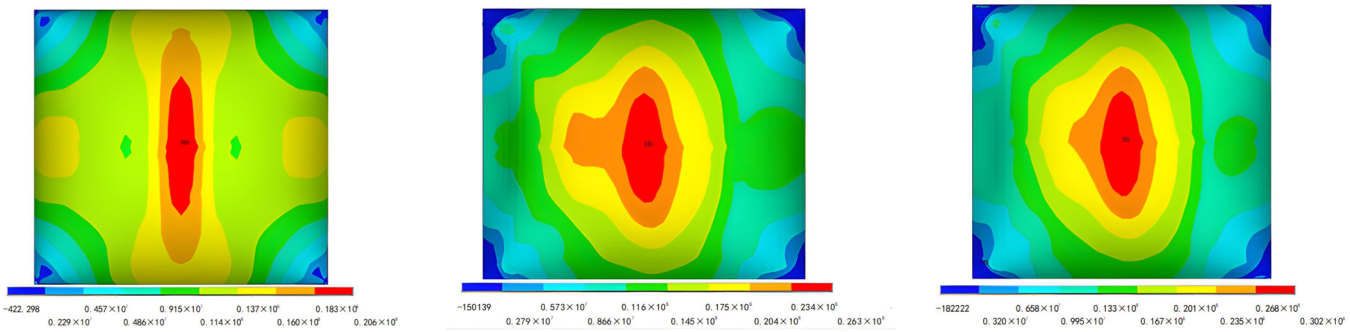


Figure 12. Schematic diagram of internal pressure in shape-finding process.

Load combination 1 indicates a strength check of the air-supported membrane coal shed under maximum working pressure, and load combination 2 indicates a strength check of the air-bearing membrane coal shed under a permanent load, internal pressure, and wind load. Load combination 3 is a strength check of the air-supported membrane coal shed under a permanent load, internal pressure, and wind and snow load. The wind load is the dominant load, so the snow load is multiplied by the combination coefficient of 0.7. The load combination analysis of the air-supported membrane coal shed is carried out, and the stress distribution of the membrane surface under the action of load combination 1 is shown in the following Figure 13a. Taking a 0-degree angle as an example, the stress distribution of the membrane surface under the action of load combination 2 and 3 is shown in Figure 13b,c below.



(**a**) Load combination 1 (**b**) Load combination 2 (**c**) Load combination 3

Figure 13. Stress distribution of load combinations 1, 2, and 3 on the membrane surface.

From the figure, it can be seen that the maximum stress on the membrane surface under the combination of internal pressure and a permanent load is 20.6 MPa in the case of air-supported membrane coal scaffolding without external loads. At this time, the maximum internal pressure of the subdivision coefficient is 1.3, so the gas-supported membrane coal scaffolding meets the strength standard in the case of no external loads. Under a wind angle of 0 degrees, the stress on the membrane surface is 26.3 MPa and 30.2 MPa when load combinations 2 and 3 are applied to the membrane surface.

In summary, for the same load combination, the maximum stress and the maximum displacement of the membrane surface of the air-supported membrane coal shed are different under different wind angles; for different wind angles, the maximum displacement and the maximum stress of the membrane surface obtained by different load combinations are close to the trend of the change in the wind angle.

5. Conclusions

In this study, the optimization design of an air-supported membrane coal shed structure is studied. Firstly, two optimization solutions are proposed and compared, and a

multi-objective optimization model is established with the objectives of minimum maximum stress, most uniform stress distribution, minimum maximum displacement, and the lowest cost possible. By combining MATLAB and ANSYS, the improved NSGA-II algorithm is designed to solve the model optimally, and the optimized scheme under a uniform load is obtained, which reduces the maximum stress on the loaded membrane surface by 5.36%, shortens the maximum displacement under the load by 30.3%, and saves 9.85% of the project cost compared with the initial scheme. The validation of the actual project data shows that the joint optimization method can provide better solutions in the design of the air-supported membrane coal shed structure compared with the engineering empirical value design. It has high feasibility and practicality.

At the same time, there are challenges in this research direction, and future research could consider more realistic and detailed, simplified models of air-supported membrane coal shed structures, including the effects of the import and export systems and other connecting components, in order to more accurately assess their load-bearing performance. Improvement of the load-bearing performance can start from the aspects of mechanical properties of the materials and optimization of the structural design, and in-depth research should be performed on methods to improve the strength and stability of the structure. In addition, the standardized analysis system is also an important development direction for the air-supported membrane coal shed structure, and future research can be devoted to the establishment of a perfect structural analysis method for wind, snow, and other loading environments in order to meet the needs of engineering practice and improve the design level. With the diversification of environmental loads in practical applications, such as wind and rain, snow pressure, temperature changes, etc., the structural stability of coal sheds is subject to higher requirements. Therefore, we must continue to conduct in-depth research to ensure that the structural design of coal sheds is both comprehensive and reliable, so as to guarantee the safety and efficiency of coal storage.

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