Optimization of Bridge Crane Main Beam Dimensions Based on Sparrow Search Algorithm and Finite Element Analysis

Yaoguang Gao [1], Qilin Zhang [2, #], Zhenming Xu [2, *, #]

[1] School of Mechanical Engineering, Guangxi University, Nanning, China, 530004

[2] Century College, Beijing University of Posts and Telecommunications, Beijing, China, 102101

* Corresponding Author Email: xuzhenming84@outlook.com

[#] These authors contributed equally.

Abstract. With the development of information technology, mathematical statistics methods have been widely used in the optimization of mechanical components. This study optimizes the main beam of a bridge crane based on the sparrow search algorithm and finite element analysis. The size of the main beam of a bridge crane has a significant impact on its structural strength and stability, making the optimization of this problem practically significant. Firstly, different sizes of main beams are simulated using finite element analysis under the most critical working conditions to obtain their structural stress and deformation. Then, the Sparrow Search Algorithm is introduced as the optimization algorithm to obtain the optimal size of the main beam through iterative solving. Finally, the effectiveness and superiority of the Sparrow Search Algorithm in the optimization of the main beam of a bridge crane are validated by comparing it with traditional optimization algorithms. Experimental results demonstrate that the optimization of the main beam of a bridge crane based on the Sparrow Search Algorithm and finite element analysis can effectively improve the structural performance of the main beam, offering certain engineering application value.

Keywords: Sparrow Search Algorithm; Bridge Crane; Optimization; Main Beam.

1. Introduction

The bridge crane is the lifting equipment for lifting materials across the workshop, warehouse, and storage yard. It is the most common category of all cranes, and it is the crane with the widest range of use and the largest number of productions in all lifting equipment [1, 2]. Among them, the main beam structure of the bridge crane is the most important part to bear the load in the operation process, accounting for about 60% of the total mass, so it is very important to achieve structural optimization of the main beam [3].

At present, the structure and size optimization of relevant mechanical parts based on mathematical and statistical methods have been widely used. By orthogonal optimization design, Hu Chengliang et al. [4] took the key parameters of the design of four gear forging dies as the design variables and carried out multi-objective optimization of the design parameter combination, reducing the machining allowance of the end face of the gear parts. Zhang Liangyou et al. [5] used the response surface analysis method to carry out the lightweight design of the main beam of the bridge crane. These traditional optimization methods are not accurate enough, have low efficiency, and cannot get ideal results. The operating environment of the crane is often more complex, so choosing intelligent optimization is more conducive to getting the global optimal solution.

For the time being, the more commonly used optimization algorithms are the genetic algorithm, the simulated annealing algorithm, and the particle swarm optimization algorithm, but this kind of algorithm has great limitations; for example, the realization of programming is more complex, the search speed is slow, there are too many parameters, and so on [6].

In recent years, the Sparrow Search Algorithm (SSA) proposed by Xue et al. [7] has the advantages of strong optimization ability, high optimization accuracy, and fast convergence speed, so it has been applied by many scholars in the field of structural optimization. For example, Qiu Weijian et al. [8] have improved the antiknock performance of sandwich panel structures based on the Sparrow Search Algorithm. Liu et al. [9] solved the UAV route planning problem based on the Sparrow Search

Algorithm; Wumaier et al. [10] realized the fault diagnosis of wind turbine units by using the Sparrow Search Algorithm.

In conclusion, based on Sparrow Search Algorithm and finite element technology, this paper optimizes the structural dimension parameters of the crane. While reducing the maximum equivalent stress, the performance of the main beam of the crane can be improved as much as possible and its service life can be extended.

2. Static analysis model of the main beam of the overhead crane

2.1. Creation and simplification of three-dimensional models

An overhead crane with a rated lifting capacity of 32t, a span of 25.5m, a working grade of A5, and a manufacturing material of Q235 was selected as the research object. The basic parameters of the main beam are shown in Table.1.

Table 1. The basic parameters.

Parameter Name	Parameter Values	Unit of Parameter
Span	25.5	m
Rated lifting capacity	30	t
Lifting height	12	m
Small car wheelbase	3850	mm
Large wheelbase	25.5	m
The weight of a single main beam	10.305	t
Small wheel press F_1, F_2	117600	N

The main beam is a regular box beam, so its span middle cross-section is shown in Figure 1, and the parameter values of the cross-section are shown in Table.2.

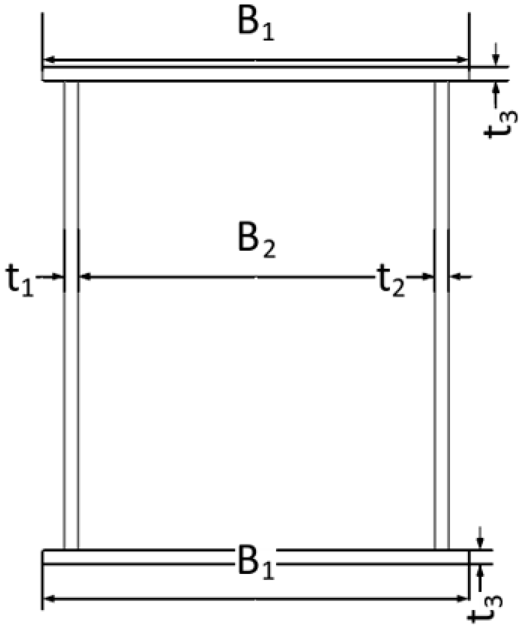

Figure 1. Middle cross-section of the main beam.

Table 2. The basic parameters.

Parameter name	Parameter value	Parameter units
Thickness of upper and lower flange plates	22	mm
Width of upper and lower flange plates	600	mm
Rail side web thickness	8	mm
Thickness of the off-track web	6	mm
Beam medium height	1450	mm

Because the crane is enormous and its structure and design are very complex, it will greatly affect the efficiency and calculation of finite element analysis and the results of simulation analysis. In order to improve the experimental efficiency and reduce the impact of unimportant components on the simulation process, it is very necessary to simplify the composition of the main beam of the overhead crane, such as by ignoring the small partitions and stiffeners in the main beam that have little effect on the stability, static stiffness, and static strength of the main beam [11]. In order to conform to the actual working conditions as much as possible, the main beam is only equipped with large partitions. The simplified main beam model is shown in Figure 2.

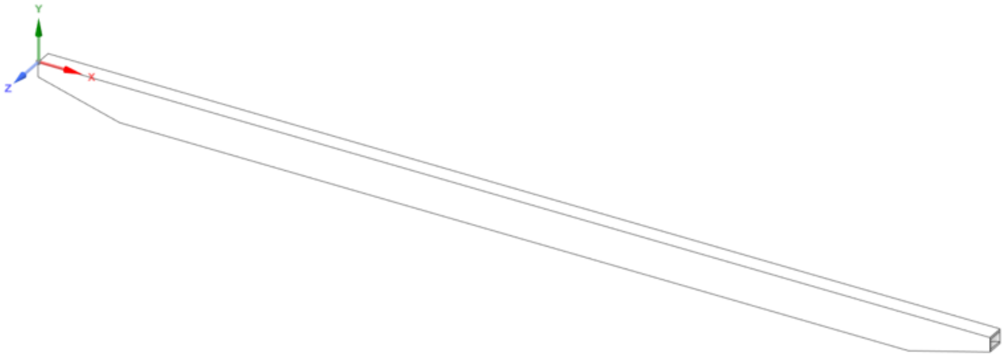

Figure 2. Simplified model.

2.2. Finite element analysis

The Solidworks overhead crane ground main beam was used for 3D modeling, and the 3D model of the main beam was imported into Workbench for finite element analysis. Before the static analysis, it is necessary to set the material parameters of the main beam, and the specific parameter settings are shown in Table.3.

Table 3. Value of parameters.

material	Modulus of Elasticity/MPa	Yield Strength/MPa	Poisson's ratio	Density/(kg/m^3)
Q235	2.1×10^5	135	0.3	7850

The tetrahedral method and patch conformal algorithm were used to mesh the main girder of the overhead crane, and the model after meshing had a total of 452090 nodes and 225812 tetrahedral elements.

Fixed constraints are set at both ends of the main beam. The self-weight of the main beam is achieved by setting a standard gravity acceleration. The load on the main beam is applied to the area where the upper cover of the main beam is in contact with the trolley track [12]. The fully loaded trolley span is the most dangerous working condition, and the wheelbase of the trolley is 3850mm, so two-wheel pressures are applied at two points with a spacing of 3850mm on the main beam, and the size is 117600N. The simplified mechanical model of the main beam under the most dangerous working conditions is shown in Figure 3.

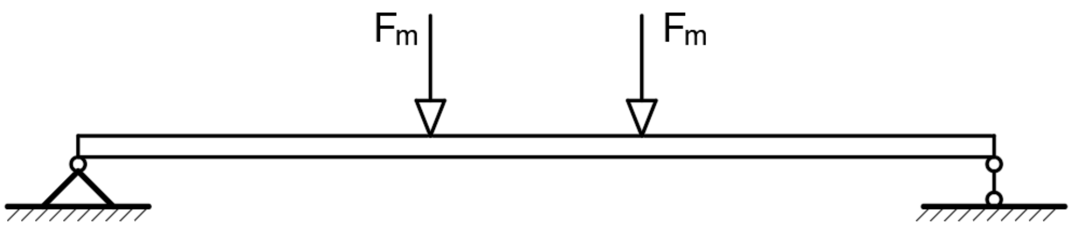

Figure 3. Simplified mechanical model.

The iso-effect force cloud diagram of the main beam is shown in Figure 4. As can be seen from Figure 4, the maximum equivalent force of the main beam is 808.21 MPa.

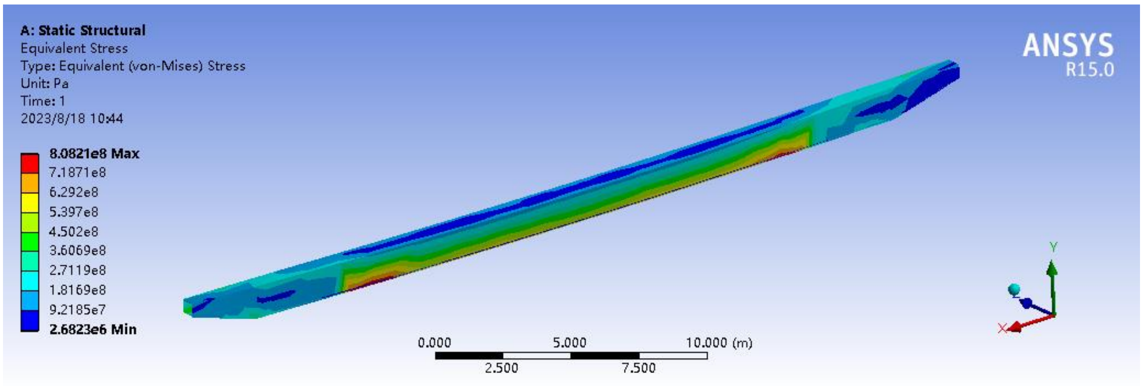

Figure 4. Analysis results without optimization.

3. Design of optimized size of main beam

3.1. Mathematical model

The goal of optimizing the size of the main beam in this paper is to make the maximum equivalent force of the main beam under the most dangerous conditions as small as possible. The structure of the main beam is checked using the limit-state method.

$$\min F(X), \tag{1}$$

$$s.t.g\ A \le M(X) \le B, \tag{2}$$

$$X = [x_1, x_2, x_3, x_4], \tag{3}$$

F(X) is the maximum equivalence force function of the main beam, M(X) is the constraint of the cross-sectional area, A and B are constants, and [x_1, x_2, x_3, and x4] are the design variables.

3.2. Parameter design

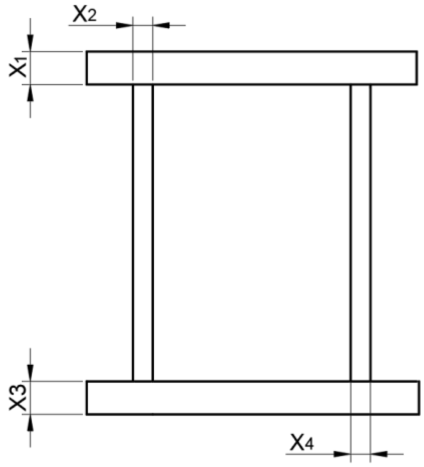

Figure 5. Middle cross-section of the main beam.

Different structural sizes have different effects on the analysis results and will affect the larger size setting parameters, including upper flange thickness x_1, rail side web thickness x_2, lower flange plate thickness x_3, and non-track side web thickness x_4, as shown in Figure 5.

3.3. Sparrow Search Algorithm

Sparrow Search Algorithm is a heuristic search algorithm based on the ecological behavior of sparrows in nature [13]. The algorithm simulates the behavior of sparrows when looking for food and establishing territory, and is applied to solve optimization problems.

The basic idea of the Sparrow Search Algorithm is to continuously update the current optimal solution by simulating the search behavior of multiple individual sparrows. Sparrow populations are divided into three roles: discoverer, follower, and watchman.

Finders have good adaptation; they prioritize access to food and provide directions to the entrant. So, finders can search on a wider range. The location of the finder is updated as shown in Equation (4).

$$X_{i,j}^{t+1}=\begin{cases} X_{i,j}^{t}\bullet \exp\left(-\dfrac{i}{\alpha\bullet I_{iter\max}}\right),\ if\ R_2<ST \\ X_{i,j}^{t}+Q\bullet L,\ if\ R_2\geq ST \end{cases} \tag{4}$$

Followers increase their predation rate by following the finder in search of food, sometimes snatching food with the finder, and the position of the joiner is updated as shown in Equation (5).

$$X_{i,j}^{t+1}=\begin{cases} Q\bullet \exp\left(\dfrac{X_{worst}^{t}-X_{i,j}^{t}}{i^2}\right),\ \ if\ i>\dfrac{n}{2} \\ X_{P}^{t+1}+\left|X_{i,j}-X_{P}^{t+1}\right|\bullet A^{T}(AA^{T})^{-1}\bullet L,\ \ otherwise \end{cases} \tag{5}$$

Vigilantes account for 10% ~ 20% of the total number of sparrows, and they can be aware of the danger. The position of the vigilant is updated as shown in Equation (6).

$$X_{i,j}^{t+1}=\begin{cases} X_{best}^{t}+\beta\bullet\left|X_{i,j}^{t}-X_{best}^{t}\right|,\ \ if\ \ f_i\neq f_g \\ X_{i,j}^{t}+K\bullet\left(\dfrac{X_{i,j}^{t}-X_{best}^{t}}{\varepsilon+(f_i-f_w)}\right),\ \ if\ \ f_i=f_g \end{cases} \tag{6}$$

The Sparrow Search Algorithm has better global searching ability and fast convergence in dealing with many kinds of good performance optimization problems. The specific flow of the Sparrow Search Algorithm is shown in Figure 6.

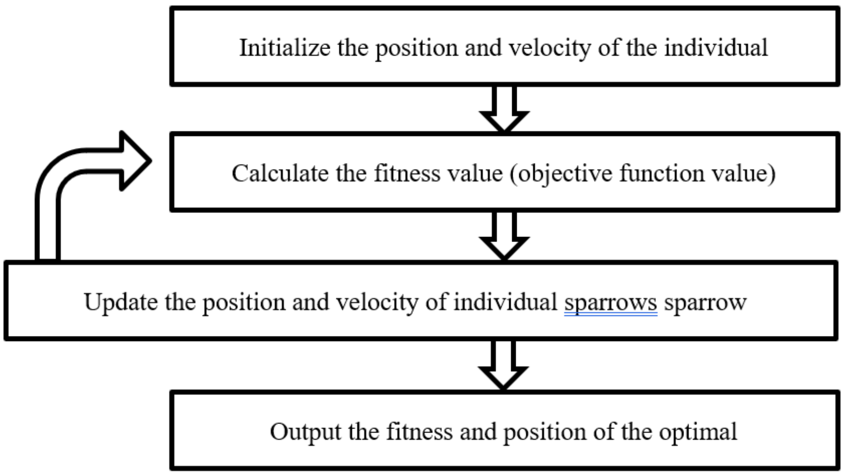

Figure 6. The flow of the SSA.

4. Numerical experiment and result analysis

4.1. Experimental protocol and data collection

In this paper, the experimental design scheme of four-factor five-level orthogonality is adopted, and the four variables x_1, x_2, x_3, and x_4 designed in 3.2 are, respectively, brought into the appropriate five-orthogonal table, as shown in Table.4.

Table 4. Scheme of four-factor five-level orthogonality.

Numbering	x_1	x_2	x_3	x_4
1	22	8	22	8
2	22	16	66	32
3	22	24	110	16
4	22	32	44	40
5	22	40	88	24
6	44	8	110	32
7	44	16	44	16
8	44	24	88	40
9	44	32	22	24
10	44	40	66	8
11	66	8	88	16
12	66	16	22	40
13	66	24	66	24
14	66	32	110	8
15	66	40	44	32
16	88	8	66	40
17	88	16	110	24
18	88	24	44	8
19	88	32	88	32
20	88	40	22	16
21	110	8	44	24
22	110	16	88	8
23	110	24	22	32
24	110	32	66	16
25	110	40	110	40

The 25 groups of main beams of different sizes were 3D modeled by solid work, and the models were imported into the Workbench for static analysis. The total maximum equivalent force and deformation of the main beam at different sizes was obtained as shown in Table.5.

Table 5. Analysis result.

Numbering	x1	x2	x3	x4	Total deformation (m).	Maximum stress(N)
1	22	8	22	8	0.1189	6.4294E+08
2	22	16	66	32	0.050947	2.2462E+08
3	22	24	110	16	0.4572	2.2418E+08
4	22	32	44	40	0.49186	1.9363E+08
5	22	40	88	24	0.042414	1.9020E+08
6	44	8	110	32	0.036621	1.7765E+08
7	44	16	44	16	0.052241	1.8913E+08
8	44	24	88	40	0.034719	1.4990E+08
9	44	32	22	24	0.05981	2.4776E+08
10	44	40	66	8	0.042736	1.6980E+08
11	66	8	88	16	0.036784	1.5787E+08
12	66	16	22	40	0.057669	3.3945E+08
13	66	24	66	24	0.036463	1.3468E+08
14	66	32	110	8	0.032653	1.3707E+08
15	66	40	44	32	0.037201	1.3357E+08
16	88	8	66	40	0.33434	1.6153E+08
17	88	16	110	24	0.28379	1.1331E+08
18	88	24	44	8	0.044035	2.3795E+08
19	88	32	88	32	0.028602	9.7312E+07
20	88	40	22	16	0.055999	3.8298E+08
21	110	8	44	24	0.040811	2.1415E+08
22	110	16	88	8	0.031085	1.4406E+08
23	110	24	22	32	0.047664	2.2919E+08
24	110	32	66	16	0.032308	2.9305E+08
25	110	40	110	40	0.023939	8.4673E+07

4.2. Size optimization based on Sparrow Search Algorithm

The SPSS software is used to nonlinearly fit the maximum equivalence force and four factors on the main beam, and the polynomial fitting function form is selected:

$$F = a\bullet x_1^2 + b x_2^2 + c\bullet x_3^2 + d\bullet x_4^2 + a1\bullet x_5\bullet x_2 + b1\bullet x_1\bullet x_3 + c1\bullet x_1\bullet x_4 + d1\bullet x_2\bullet x_3 + e1\bullet x_2\bullet x_4 + f1\bullet x_3\bullet x_4 + a2\bullet x_1 + b2\bullet x_2 + c2\bullet x_3 + d2\bullet x_4 + m \quad (7)$$

After importing the data from Table.5 into SPSS, the estimated values of each parameter are shown in Table.6.

Table 6. The estimated values of parameters.

Parameters	Estimated value	Standard error	95% confidence interval Lower	95% confidence interval Upper
a	29451.728	19880.599	-14845.007	73748.463
b	206356.795	150347.038	-128637.281	541350.871
c	41135.203	19880.598	-3161.530	85431.936
d	23903.550	150346.844	-311090.095	358897.195
a1	99198.499	50595.348	-13534.962	211931.960
b1	-3715.013	18398.311	-44709.003	37278.978
c1	-64653.024	61540.963	-201774.834	72468.786
d1	72825.474	61540.956	-64296.321	209947.269
e1	-144979.280	139137.206	-454996.293	165037.734
f1	25455.281	50595.338	-87278.157	138188.719
a2	-5346121.468	4034243.173	-14334975.420	3642732.484
b2	-19848160.388	11094171.704	-44567515.392	4871194.615
c2	-9761541.375	4034243.051	-18750395.055	-772687.695
d2	1943828.255	11094158.444	-22775497.203	26663153.714
m	989021727.660	132269651.546	694306578.111	1283736877.209

Table 7. Anova.

Source	Quadratic sum	DOF	Mean square
Regression	1.384E+18	15	9.229E+16
Residual	4.218+16	10	4.218E+15
Total before correction	1.427E+18	25	
Revised total	3.154E+17	24	
Dependent variable:Maximum equivalent stress(N)			
R^2 = 1 - (residual sum of squares) / (modified sun of squares) = 0.866.			

As can be seen from Table.7, the R^2 of the nonlinear fitting result performed by SPSS, which has high fitting accuracy, is 0.866.

Bring the nonlinear fitting results into the Matlab code of the SSA and set the parameters of the optimization algorithm to 100 population sizes and 100 maximum iterations. The area of the cross-section is constrained by setting dimensional constraints; the specific constraints are: x_1 upper value 28, lower limit value 20mm; P_2 upper limit value 10, lower limit value 8mm; x_3 upper limit value 22mm, lower limit value 12mm; the upper value of x_4 is 10, and the lower limit is 6mm.

The change in population fitness values during iteration is shown in Figure 7.

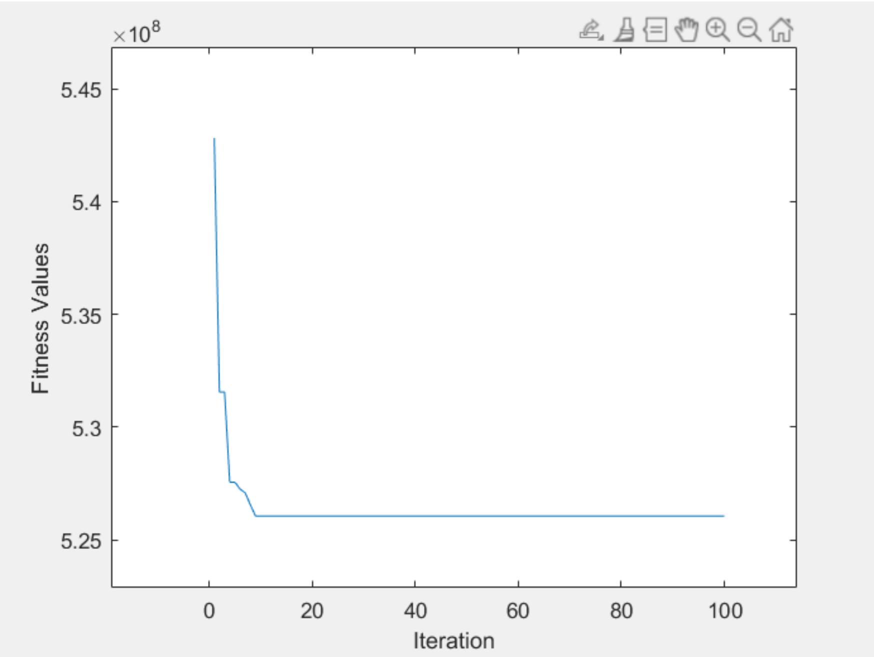

Figure 7. The change in population fitness values.

4.3. Analysis and verification of optimization results

The main beam optimization results are shown in Table.8.

Table 8. Optimization results.

Parameter	x_1	x_2	x_3	x_4
Value/mm	28	10	22	10

SolidWorks was used to model the optimization results of the main beam size, and the model was imported into Workbench for static analysis, and the static analysis results were shown in Figure 8.

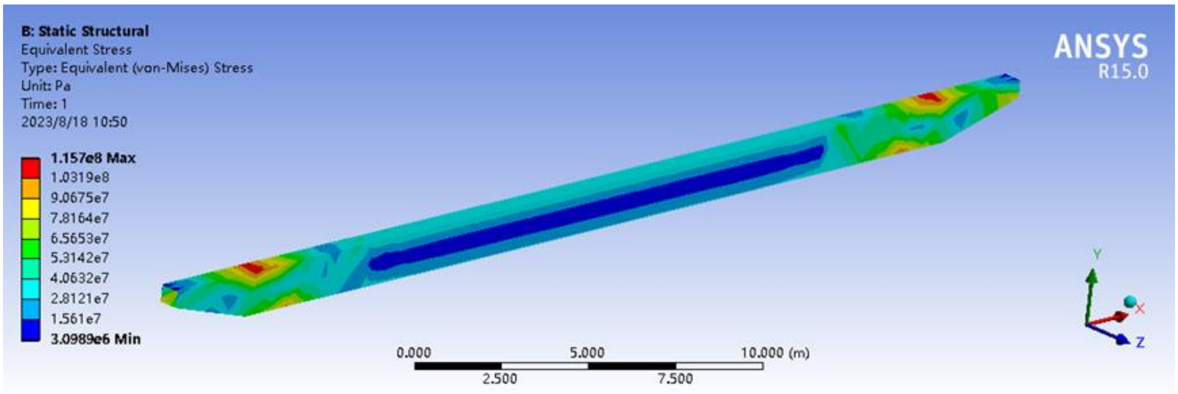

Figure 8. Analysis results of optimization.

The static analysis results show that the maximum equivalent force of the main beam after size optimization is 115.7 MPa. Compared with the main beam before optimization, the maximum equivalent force of the main beam after size optimization under the most dangerous working conditions is greatly reduced, and the optimization result is more ideal.

5. Conclusions

In conclusion, this study optimized the main beam of a bridge crane based on the combination of the Sparrow Search Algorithm and finite element analysis. By using finite element analysis, the stress and deformation of main beams with different sizes were simulated under the most critical working conditions. The relationship between the maximum equivalent stress and important structural dimensions was fitted. Subsequently, the Sparrow Search Algorithm was introduced as an optimization algorithm to iteratively solve for the optimal dimensions of the main beam. Compared with traditional optimization algorithms, the Sparrow Search Algorithm demonstrated better performance and superiority in the optimization of main beams for bridge cranes. Experimental results showed that the optimization of the main beam of a bridge crane based on the Sparrow Search Algorithm and finite element analysis effectively improved the structural performance of the main beam, which has certain engineering application value. Therefore, this study provides an effective and feasible method for optimizing the main beam of a bridge crane, which is of great significance for enhancing the safety and reliability of cranes. Future research can further explore the application of the Sparrow Search Algorithm in other engineering optimization problems and compare it with more optimization algorithms to further improve and optimize the design and performance of the main beam of bridge cranes.

References

[1] Wang Zhibin, Zhang Yang, Zhou Guopeng, et al. FEM analysis and structure optimization of main beam of double beam bridge crane %J Machine Design and Manufacturing Engineering [J]. 2022, 51(07): 19-23.

[2] Li Zuobin, Cao Xuyang, Wang Peng, et al. The Design for a New Type of Girder of Overhead Crane Based on Topology Optimization %J Machinery Design & Manufacture [J]. 2017, (10): 175-8.

[3] Gao Hailian. The Design of Multi-Objective Optimization of Main Beam of 480t Bridge Crane [D]; Harbin University of Science and Technology, 2019.

[4] Hu Chengliang, Liu Quankun, Wang Qiang, et al. Multi-objective Optimal Design of the Gear Forging Die Based on Grey Relational and Fuzzy Logic %J China Mechanical Engineering [J]. 2007, (14): 1739-42.

[5] Zhang Liangyou, Wang Yahu, Ju Chao, et al. Lightweight design of bridge crane girder based on response surface analysis %J Chinese Journal of Construction Machinery [J]. 2021, 19(05): 462-5.

[6] Ge yihang, Yang Guangyong, Yu Yuanjie, et al. Mobile robot path planning based on improved SSA %J Transducer and Microsystem Technologies [J]. 2023, 42(07): 132-5.

[7] Xue Jiankai. Research and Application of a Novel Swarm Intelligence Optimization Technique: Sparrow Search Algorithm [D]; Donghua University, 2020.

[8] Qiu Weijian, Liu Kun, Zhang Xinyu, et al. Anti-explosion performance optimization method of sandwich panel structure based on BP-SSA algorithm %J Ship Science and Technology [J]. 2022, 44(07): 25-30.

[9] Liu G Y, Shu C, Liang Z W, et al. A Modified Sparrow Search Algorithm with Application in 3d Route Planning for UAV [J]. Sensors, 2021, 21(4).

[10] Wumaier T, Xu C, Guo H Y, et al. Fault Diagnosis of Wind Turbines Based on a Support Vector Machine Optimized by the Sparrow Search Algorithm [J]. Ieee Access, 2021, 9: 69307-15.

[11] Tan Yunbo. The Research on Analysis and Optimization of Dynamic Stiffness of Large Span Double Beam Bridge Crane [D]; Cerntral South University of Forestry & Technolohy, 2017.

[12] Huang Rongxing, Wang Huqi, Luo Xirong. Finite element analysis and structural development of the bridge crane girder based on ANSYS %J Mechanical research & application [J]. 2012, (06): 52-4.

[13] Xue J K, Shen B. A novel swarm intelligence optimization approach: sparrow search algorithm [J]. Systems Science & Control Engineering, 2020, 8(1): 22-34.