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ABSTRACT

In the field of cranes, unreasonable structure design leads to high energy consumption. In order to solve the problems of heavy weight and serious steel consumption of a crane structure, a green energy-saving design method based on computational intelligence is proposed. For minimizing the weight of a structure, two optimization models are proposed. The specular reflection algorithm is used to make the green and lightweight design. A multi-objective optimization model for the green design is constructed. The minimum waste generated in the manufacturing process is the objective function of this model. Fuzzy mathematics theory is utilized to comprehensively evaluate the impact of crane structure weight and processing waste on the environment, and a structural optimization model with fuzzy comprehensive evaluation indicators for the green design is introduced. The results indicate that compared with the original design, the processing waste after fuzzy comprehensive optimization is 63.43% lower and the cross-sectional area of the main girder is reduced by 27.03%.

I. INTRODUCTION

A bridge crane is a kind of lifting equipment that spans workshops, warehouses, and material yards for material handling. It is widely used in national defense, logistics, and other fields. It is an indispensable important mechanical equipment for industrial production. The complete life cycle of a bridge crane consists of the following three parts: (i) manufacturing, (ii) service, and (iii) scrapping. Overhead cranes affect the environment in these three stages, such as energy consumption and pollutant discharge. The energy consumption and pollution problems of the above three stages can all be improved through design-related indicators. For example, the lightweight design can reduce energy consumption to a certain extent, reduce machining and cutting waste, and improve material utilization. Therefore, it is very important to reduce the impact of the crane on the environment through the lightweight design. With the increasing complexity of the design model, the introduction of an intelligent optimization algorithm in the design process can significantly improve the design efficiency. The meta-heuristic algorithm is popular among engineers and researchers because of its simple principle, no gradient information, and strong search ability. The meta-heuristic algorithm builds the search model according to the biological behavior or physical phenomenon. It can be divided into the genetic evolution-based algorithm, physical phenomenon-based algorithm, and population-based algorithm. The Genetic Algorithm (GA) is the representative of the algorithm based on genetic evolution. Inspired by Darwinian evolution, the algorithm combines the best individuals in each iteration to enhance the competitiveness of the population.[1] The classical algorithm based on the physical phenomenon is the Simulated Annealing (SA) algorithm, which is inspired by the change of the particle state in solid during the process of heating and cooling.[2] The most popular population-based algorithm is Particle Swarm Optimization (PSO). Particle swarm optimization imitates the social behavior of birds to get the optimal solution.[3] With the continuous development of the meta-heuristic algorithm, the whale optimization algorithm,[4] the black hole optimization,[5] the gray wolf optimizer,[6] and other new algorithms are proposed and applied in various fields.

In terms of lightweight and energy-saving design, many researchers have carried out various analyses from different angles and achieved some positive results: Ai-kui[7] used TRIZ (Theory of The Solution of Inventive Problems) theory to design large-scale presses with energy-saving targets and solved the problem of rapid energy-saving of heavy-duty presses. Yan *et al.*[8] integrated the methods of optimized design and parametric design into the crane design system, and the quality of the whole machine was reduced by 10.5%, which saved costs and achieved the purpose of energy saving. Li *et al.*[9] provided a feasible design strategy for offshore wind energy hybrid energy regeneration by establishing a multi-objective optimization problem. Liu *et al.*[10] adopted the response surface method to design a lightweight pre-bending machine, which reduced the consumption of raw materials and achieved the purpose of energy saving. Le *et al.*[11] used the firefly algorithm to discretely optimize the green design of the truss structure and achieved good energy-saving effects, providing a new method for the green design. Kumar *et al.*[12] adopted multi-objective optimization and gray fuzzy logic methods to reduce the amount of metal chips generated during the traditional drilling process and achieved the purpose of energy saving. Han *et al.*[13] used an improved particle swarm optimization algorithm to optimize the multi-material layout of the truss structure, appropriately using expensive and strong materials locally, reducing the total energy consumption of the multi-material structure. Ouyang and Zhang[14] took the bin-type automatic warehouse as the research object, used the genetic algorithm to solve the problem, designed and planned a more reasonable storage area, reduced the energy consumption of the automatic warehouse, and improved the energy saving and practical operation. Cost savings provide a basis. Sun *et al.*[15] took the under-driven crane as the research object and proposed a transportation control method of the double pendulum crane with the lowest energy consumption as the goal, which reduced the energy consumption during the operation of the crane. Wu *et al.*[16] proposed a staged topology optimization design method for the truss structure, which realized the size optimization of the tower crane jib structure, reduced the use of raw materials, and realized energy saving and emission reduction. Savković[17] proposed a new type of bionic optimization algorithm through the optimization design of the box section of the main girder of the single-girder bridge crane, effectively reducing the structural weight and achieving the goal of energy saving. Ang and Liu[18] used super-element technology to optimize the crane frame structure, which effectively reduced the calculation time and provided a feasible new idea for the lightweight structure. Almeida *et al.*[19] proposed a method to optimize anisotropic composite structures. On the basis of topology optimization, the cross section parameters of the composite structure were optimized, which improved the stiffness of the structure while reducing weight. Zhang *et al.*[20] proposed a bionic bamboo beam composed of bionic bamboo tubes and bionic bamboo membranes and established a lightweight design of bionic bamboo beams using response surface methodology, which provided a new idea for the design of lightweight beam structures. Feng Guo-qing *et al.*[21] used a variety of intelligent optimization algorithms to optimize the design of large-scale ship structures under complex constraints. The mid-section area of the example ship was reduced, materials were saved, and energy consumption was reduced. Ali and Toğan[22] used an integrated particle swarm optimization algorithm to optimize the size and layout of the truss structure under dynamic constraints, providing a basis for the optimal energy-saving design of the truss structure. Based on the energy consumption of bridge cranes in the whole life cycle, Wei *et al.*[23] used the fuzzy evaluation model to analyze and evaluate the energy consumption of cranes with different designs and materials based on the energy consumption of the bridge crane in the whole life cycle, providing a feasible design for the energy-saving design of cranes. Theory and method: Hayajneh *et al.*[24] studied the influence of submerged arc welding on the bending deformation of I-beams. Through reasonable selection of appropriate welding process parameters, the welding deformation can be minimized, thereby providing a way for the structural design and energy saving. Novel solutions: Skoglund *et al.*[25] applied high-strength steel to bridge structures. Research has shown that the use of high-strength steel can save a lot of weight, environmental impact, and material costs. Kaveh *et al.*[26] put forward a new combination of swarm intelligence and chaos theory, improved the particle swarm algorithm, and provided a feasible new method for the optimization of a truss structure. Chwastek[27] aimed at the problem of Euler and Coriolis forces caused by material handling operations and proposed a method for solving the minimum value of the functional function, which provides a new idea for the comprehensive global optimal analysis of the mechanical product structure. Elhewy[28] used the finite element analysis method to optimize the design of a ship structure and applied blind search optimization technology. By comparing the weights of various design schemes, the weight reduction effect was significant, and the use of materials was reduced. The goal of saving energy and reducing costs. Hasançebi and Carbas used the bat algorithm to carry out the discrete optimization design of the truss structure and proved that the bat algorithm is very efficient in solving the discrete optimization problem.[29] Liu *et al.*[30] designed a main support structure for a deep space exploration camera and adopted a topology optimization method to lighten the structure. The weight reduction rate of the front and rear frame structure reached more than 90%, and the optimized structure has a relatively high weight. High stability and reliability: Kovacs[31] aimed at minimizing the cost of the crane box girder structure and optimized the crane structure. The optimization model is of great significance for reducing the cost of the crane.

The current crane structure design lacks research on material consumption and processing waste. This paper establishes two crane structural design models. The steel plate blanking and cutting process before the crane structure welding is studied. With the goal of minimizing the cutting allowance of the following steel plates, a crane structure optimization design model was established. The specular reflection algorithm is used to optimize the structure of the discrete variable model. Combined with the traditional lightweight design model, a fuzzy comprehensive optimization design model of the crane structure is established. This model can significantly reduce the waste generated in the production process of the crane mechanism. The results show that the new design model can significantly improve material utilization and reduce energy consumption. This model can be popularized and applied in crane design and manufacturing.

II. CRANE STRUCTURE DESIGN

In the crane manufacturing process, the material consumption of the crane structure has an important impact on the environment. The design of structural products determines the carrying capacity

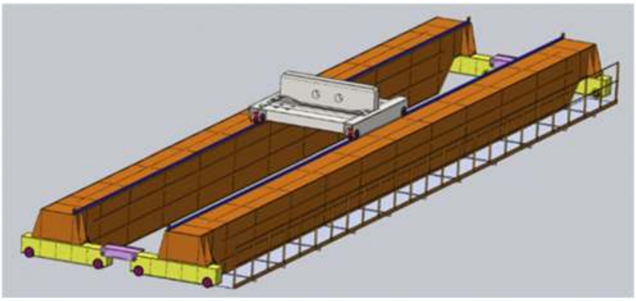

FIG. 1. Crane structure model.

TABLE I. Overall design parameters.

No.	Term	Value	Unit
1	Span	22 500	mm
2	Lifting capacity	20	t
3	Lifting height	18	m
4	Lifting speed	30	m/min
5	Working level of the crane	A7	⋯
6	Wheelbase of the trolley	2 000	mm
7	Gauge of the trolley	6 400	mm
8	Quality of the trolley	11 000	Kg
9	Wheel pressure of the fully loaded trolley	85	KN
10	Wheel pressure of the no-load trolley	27.5	KN
11	Structural materials	Q355	⋯
12	Trolley operating limit position	19 900	mm

of cranes. A reasonable structural design can enhance the carrying capacity and the safety of cranes. Using lightweight methods to design crane structures has a tremendous influence on reducing carbon emissions during the life cycle of cranes. Therefore, the reasonable design of the crane structure using advanced design methods is necessary. Before the lightweight design of the crane structure, the traditional method is used to verify the design of the crane structure. After verification, the crane metal structure meets the requirements of strength, stiffness, and stability.

A. Structural design model

When designing the crane metal structure, first determine the basic parameters such as crane span and lifting weight. This paper takes a certain type of general-purpose bridge crane as the research object. The overall structure model of the crane is shown in Fig. 1, and some of the overall design parameters of the crane are shown in Table I. The cross section of the main girder of the crane is shown in Fig. 2. In Fig. 2, the main girder of the crane uses a box girder structure welded by four steel plates. Table II shows the size of each part of the box girder structure section. To reduce the height of the crane and use materials reasonably, the main girder structure of the bridge crane is generally designed as a variable section structure, as shown in Fig. 3. This structure can reduce the height of the crane. The end section of the main girder only bears shear

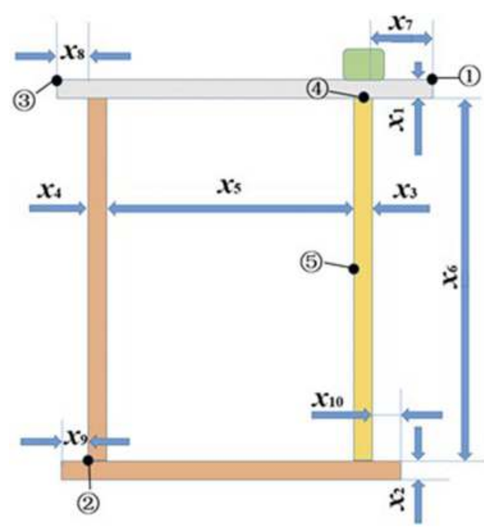

FIG. 2. Cross section of the crane main girder.

TABLE II. Optimization design variables of the main girder section.

No.	Term	Symbol	Value	Unit	Is it a design variable for optimization problems?	Calculation formula
1	Upper flange thickness	x_1	12	mm	Yes	⋯
2	Lower flange thickness	x_2	12	mm	Yes	⋯
3	Main web thickness	x_3	10	mm	Yes	⋯
4	Secondary web thickness	x_4	8	mm	Yes	⋯
5	Inner web spacing	x_5	520	mm	Yes	⋯
6	Web height (middle span)	x_6	1250	mm	Yes	⋯
	Web height (span end)	x_6	400	mm	Yes	⋯
7	Outer elongation of the upper flange plate (main web side)	x_7	60	mm	No	$x_7 = 5x_1$
8	Outer elongation of the upper flange plate (secondary web side)	x_8	30	mm	No	$x_8 = 30$
9	Outer elongation of the lower flange plate (secondary web side)	x_9	30	mm	No	$x_9 = 30$
10	Outer elongation of the lower flange plate (main web side)	x_{10}	30	mm	No	$x_{10} = 30$

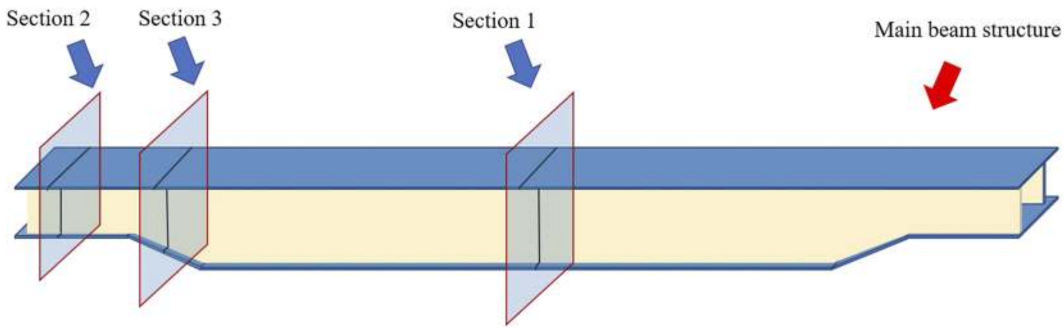

FIG. 3. Variable cross section main girder structure.

stress. Its load state is much simpler than the mid-span section of the main girder. Therefore, the main girder made of a variable cross section structure can meet the design requirements of the structure.

B. Structural mechanical model

The research object of this paper is a double-girder general bridge crane. The main girder of the crane is a skew rail box girder bridge structure. Under working conditions, the structure bears horizontal and vertical loads. The main and end girders of the bridge are rigidly connected. Under the action of vertical load, when the main girder is bent under load, the cart wheel installed on the end girder rotates around the top of the track and becomes a simply supported girder. The mechanical model of the main girder structure in the vertical direction is shown in Fig. 4. In the horizontal direction, the load on the structure is relatively small. It can be approximated as a simply supported girder, as shown in Fig. 5.

C. Structure check

The internal force of the crane in the most dangerous condition can be determined according to the load condition of the crane structure and relevant mechanical model. According to the internal force, the reasonable design method is adopted to check the structure. When the crane structure meets the requirements of strength, stiffness, and stability, the design of structural parameters is reasonable and the bearing capacity of the structure meets the design requirements. To verify the bearing capacity of each section of the crane girder structure under different working conditions, this paper uses six working conditions to design and calculate three different main girder sections. The situation of six working conditions is shown in Table III.

According to the structural design model and the known basic design parameters, the verification method shown in Table IV is used to verify the load-bearing capacity of the crane main girder structure. The structural calculation results are shown in Tables V and VI. Table V lists the static strength calculation results of four calculation points of the main girder section under six different working conditions. The calculation point position of the main girder section is shown in Fig. 2. The calculation results in Table VI are the analysis results of the fatigue strength, static stiffness, dynamic stiffness, and overall stability of the main girder.

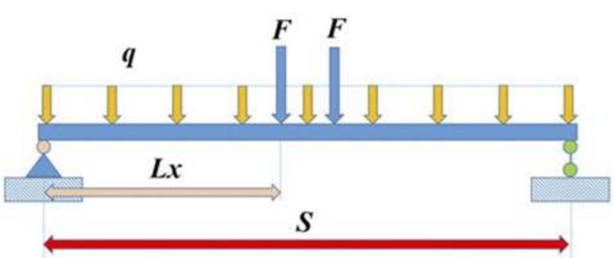

FIG. 4. Mechanical model of the main girder in the vertical direction.

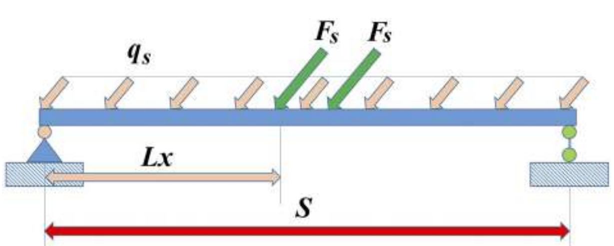

FIG. 5. Horizontal mechanical model of the main girder.

TABLE III. Six working conditions of the main girder structure calculation.

No.	Calculation section	Load status of trolley	Trolley position L_x (mm)
1	Section 1	Trolley loaded	11 250
2		Trolley empty	450
3	Section 2	Trolley empty	450
4		Trolley empty	19 900
5	Section 3	Trolley loaded	450
6		Trolley empty	19 900

TABLE IV. Crane structure checking method.

No.	Term	Check method	Symbol meaning
1	Static strength	$\sigma = \sqrt{\sigma_0^2 + \sigma_m^2 - \sigma_0\sigma_m + 3\tau^2} \leq [\sigma] = \frac{0.5\sigma_s + 0.35\sigma_b}{1.48}$	σ_0—The composite stress of the dangerous point, in N/mm^2 σ_m—The local compressive stress caused by fully loaded trolley wheel pressure, in N/mm^2 τ—Resultant shear stress caused by shear and torsion load, in N/mm^2 $[\sigma]$—The allowable stress of steel is related to the material and load combination, in N/mm^2. Since the material used in this project is Q355, the allowable stress can be checked according to the given formula σ_s—The yield point of steel, for materials without obvious yield point, $\sigma_s = \sigma_{0.2}$ ($\sigma_{0.2}$ is the test stress when the steel tensile test participates in the strain reaches 0.2%), in N/mm^2 σ_b—The tensile strength of steel, in N/mm^2
2	Fatigue strength	$\sigma_{x\max} \leq [\sigma_{xr}]$ $\sigma_{y\max} \leq [\sigma_{yr}]$ $\tau_{xy\max} \leq [\tau_{xyr}]$	$\sigma_{x\max}$—The absolute maximum compressive stress at the calculated point of the main girder, in N/mm^2 $\sigma_{y\max}$—The absolute maximum tensile stress at the calculated point of the main girder, in N/mm^2 $\tau_{xy\max}$—The maximum synthetic shear stress at the calculation point of the main girder, in N/mm^2 $[\sigma_{xr}]$—Allowable compressive fatigue stress at the calculated point of the main girder, in N/mm^2 $[\sigma_{yr}]$—Tensile fatigue allowable stress at the calculation point of the main girder, unit N/mm^2 $[\tau_{xyr}]$—Fatigue allowable shear stress at the calculation point of the main girder, unit N/mm^2
3	Static stiffness	$Y_s = \frac{P_1 + P_2}{48EI_x}\left[S^3 - \frac{b^2}{2}(3S - b)\right] \leq [Y_s]$	E—The modulus of elasticity is related to the properties of the materials used in the structure I_x—The bending moment of the main girder section in the vertical direction, in mm^4 P_1—One of the full load trolley pressures of the wheel on the side of the main girder bearing the largest load, in N P_2—One of the full load trolley pressures of the wheel on the side of the main girder bearing the largest load, in N S—The distance of the centerline of the crane carriage running track, namely the crane span, in mm. b—The distance between the two trolley wheels of the main girder on one side of the heavy machine, in mm $[Y_s]$—Allowable static displacement, in mm
4	Overall stability	$\delta = \frac{h}{b} \leq 3$	h—Spacing between flange plates of the main girder section, in mm b—The web spacing of the main girder section, in mm

III. SPECULAR REFLECTION OPTIMIZATION ALGORITHM

The specular reflection algorithm is a new intelligent optimization algorithm. Different from the general swarm optimization algorithm, the specular reflection algorithm adopts the non-population group search strategy, so the calculation process is more simplified and the calculation efficiency is higher. The specular reflection algorithm has proven to be a simple and efficient optimization method (Qisong Qi, 2015, 2017). However, in the field of engineering design, the efficiency of this algorithm needs more practice to prove. In this paper, the calculation efficiency of the specular reflection algorithm is verified and analyzed from the perspective of the lightweight design of the crane metal structure. The practical results prove that the method has the prospect of widespread application in the field of engineering design.

A. Specular reflection algorithm calculation process

The inspiration of the specular reflection algorithm comes from the phenomenon that the plane specular reflects light. The algorithm of finding the best observation position of the target object through the reflection of the ray. The specular reflection algorithm is optimized by a specific specular reflection model. The specular reflection model includes three main design factors: (i) spatial coordinates of the target object $X^{Object} = x_1^{Object}, x_2^{Object}, \ldots, x_n^{Object}$: this parameter is mainly used to determine the object being observed in space; (ii)

TABLE V. The static strength check result of the crane main girder structure.

Working condition	Item	Calculation point	Vertical bending moment	Vertical shear	Horizontal bending moment	Horizontal shear	Main girder torque	Normal stress caused by the vertical bending moment	Shear stress caused by vertical shear	Normal stress caused by the horizontal bending moment	Shear stress caused by horizontal shear	Torsional shear stress	Local compressive stress	Synthetic stress
			N·mm	N	N·mm	N	N·mm	MPa	MPa	MPa	MPa	MPa	MPa	MPa
		①						100.9430	0	11.8534	0		⋯	113.2152
		②						100.9764	2.9055	11.1238	0.3427		⋯	113.1470
1	Section 1	③	1.4058×10^9	1.0146×10^5	7.7660×10^7	5.4079×10^3	6.0001×10^7	100.9430	0	12.2765	0	5.6173	⋯	113.6367
		④						100.9430	0	9.3559	0.3732		72.4892	110.7858
		⑤						0	5.2328	9.1638	0.3732		⋯	21.4909
		①						20.1680	0	2.7089	0		⋯	23.0121
		②						20.1747	0.1032	2.5421	0.0160		⋯	22.8764
2	Section 1	③	2.8087×10^8	3.6056×10^3	1.7748×10^7	252.3889	1.5360×10^7	20.1680	0	2.8056	0	1.4380	⋯	23.1082
		④						20.1680	0	2.1381	0.0174		⋯	22.4482
		⑤						0	0.1860	2.0942	0.0174		⋯	3.5311
3	Section 2	⑤	⋯	2.5562×10^5	⋯	1.4110×10^4	6.0001×10^7	⋯	36.9668	⋯	0.7731	17.2063	⋯	95.1697
4	Section 2	④	⋯	4.6572×10^4	⋯	3.2600×10^3	1.5360×10^7	⋯	6.7349	⋯	0.1786	4.4049	⋯	19.6040
		①						61.1738	0	1.6080	0		⋯	65.7839
		②						19.9942	17.6480	1.4718	0.7590		⋯	55.8200
5	Section 3	③	1.1461×10^8	2.5374×10^5	6.3228×10^6	1.3991×10^4	6.0001×10^7	61.1738	0	1.6263	0	11.3424	⋯	65.8013
		④						61.1738	0	1.2733	0.8507		72.4892	71.2292
		⑤						0	24.8693	1.2475	0.8507		⋯	64.2062
		①						10.9810	0	0.3663	0		⋯	12.4119
		②						3.5891	3.1202	0.3352	0.1704		⋯	11.4240
6	Section 3	③	2.0573×10^7	4.4863×10^4	1.4401×10^6	3.1404×10^3	1.5360×10^7	10.9810	0	0.3704	0	2.9037	⋯	12.4157
		④						10.9810	0	0.2900	0.1910		⋯	12.4807
		⑤						0	4.3970	0.2841	0.1910		⋯	12.9790

TABLE VI. Check results of the fatigue strength, static stiffness, dynamic stiffness, and overall stability of the crane main girder structure.

	Section 1		Section 2		Section 3			
	Maximum normal stress in the vertical direction	Fatigue allowable stress	Maximum vertical shear stress	Fatigue allowable shear stress	Maximum normal stress in the vertical direction	Fatigue allowable stress	Maximum deformation in the middle of the span	Main girder aspect ratio
Calculation point	MPa	MPa	MPa	MPa	MPa	MPa	mm	⋯
②	100.9764	121.1349	⋯	⋯	19.9942	119.2735	22.0196	2.4038
⑤	⋯	⋯	36.9668	69.6530	⋯	⋯		

TABLE VII. Specular reflection model initialization.

No.	Condition	X^{Object} data transmission	X^{Mirror} data transmission	X^{Eye} data transmission
1	$f(X^1) \geq f(X^2) \geq f(X^3)$	$X^{Object} \leftarrow X^1$	$X^{Mirror} \leftarrow X^1$	$X^{Eye} \leftarrow X^1$
2	$f(X^1) \geq f(X^3) \geq f(X^2)$	$X^{Object} \leftarrow X^1$	$X^{Mirror} \leftarrow X^3$	$X^{Eye} \leftarrow X^2$
3	$f(X^2) \geq f(X^1) \geq f(X^3)$	$X^{Object} \leftarrow X^2$	$X^{Mirror} \leftarrow X^1$	$X^{Eye} \leftarrow X^3$
4	$f(X^2) \geq f(X^3) \geq f(X^1)$	$X^{Object} \leftarrow X^2$	$X^{Mirror} \leftarrow X^3$	$X^{Eye} \leftarrow X^1$
5	$f(X^3) \geq f(X^1) \geq f(X^2)$	$X^{Object} \leftarrow X^3$	$X^{Mirror} \leftarrow X^1$	$X^{Eye} \leftarrow X^2$
6	$f(X^3) \geq f(X^2) \geq f(X^1)$	$X^{Object} \leftarrow X^3$	$X^{Mirror} \leftarrow X^2$	$X^{Eye} \leftarrow X^1$

current best observation point $X^{Eye} = x_1^{Eye}, x_2^{Eye}, \ldots, x_n^{Eye}$: this parameter is mainly used to characterize the current position where the clearest object image can be observed; and (iii) spatial coordinates of the mirror $X^{Mirror} = x_1^{Mirror}, x_2^{Mirror}, \ldots, x_n^{Mirror}$: this parameter is used to simulate the position of the reflection point (mirror) X^{Mirror} in the current specular reflection model. The above three parameters constitute a basic specular reflection model. The specular reflection algorithm continuously corrects the position of the reflection point (specular) to obtain the best observation point X^{Eye} of the target object X^{Object}. Take a minimization optimization problem as an example to introduce the specular reflection algorithm:

(1) Determine design variables and objective function:
The objective function is

$$\min f(X), X = x_1, x_2, \ldots, x_n,$$

where X is a design variable and consists of n parameters.

(2) Perform random search for feasible solutions:
In the feasible domain, randomly search for three feasible design variable combinations $X^1 = x_1^1, x_2^1, \ldots, x_n^1$, $X^2 = x_1^2, x_2^2, \ldots, x_n^2$, and $X^3 = x_1^3, x_2^3, \ldots, x_n^3$. Then, the objective function values of the three feasible solutions are calculated. The initial specular reflection model is established according to the value of the objective function. The inspiration of the specular reflection model comes from the phenomenon that specular reflection light changes the propagation direction of light to obtain the best transmission path of light. The model expects to obtain the best observation effect on the target object through the least light transmission. The method of initializing the specular reflection model is shown in Table VII.

(3) Construct specular reflection to find the best observation point:
Taking X^{Mirror} as the specular reflection point, determine the incident light ray l_1 and the reflected light ray l_2, as shown in Fig. 6. α_1 and α_2 are the direction vectors of l_1 and l_2.

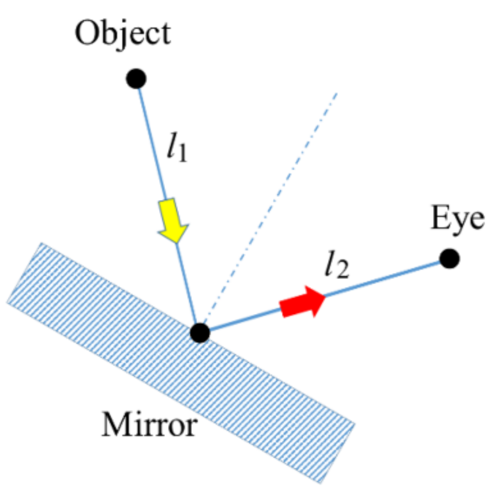

FIG. 6. Specular reflection model.

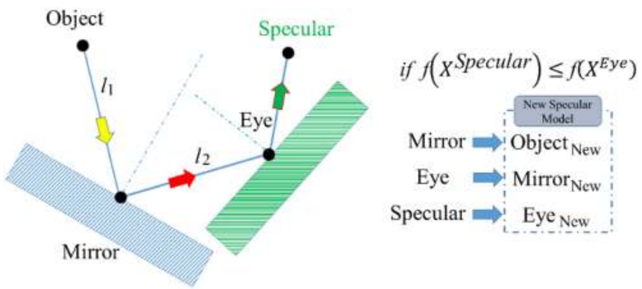

FIG. 7. New specular reflection model (condition 1).

Determine the new observation point X^{New} according to α_1 and α_2,

$$\begin{cases} \alpha_1 = X^{Mirror} - X^{Object}, \\ \alpha_2 = X^{Eye} - X^{Mirror}, \end{cases}$$

$$X^{New} = X^{Mirror} + \gamma \cdot (\beta_1 \cdot \alpha_1 + \beta_2 \cdot \alpha_2),$$

where β_1 and β_2 are the step size of the specular reflection search, $\beta_1, \beta_2 = 2rand - 1$. $rand$ is a random number, $rand \in [-1, 1]$ γ is the step-length expansion coefficient, and its value needs to be analyzed according to specific problems. Generally, $\gamma = 0.8$–2.2.

(4) Determine the new specular reflection model:
According to the new observation point X^{New} and the original specular reflection model X^{Mirror} and X^{Eye}, determine the new specular reflection model. There are three ways to determine the new specular reflection model, as shown in Figs. 7–9.

(5) Evaluate the search process:
If the search process meets the iteration termination condition, the result is output and the calculation is terminated. If the termination conditions are not met, return to the previous step to construct a new specular reflection model. The iterative termination condition of the specular reflection algorithm is determined by the maximum number of iterations and the calculation accuracy of the objective function,

$$\begin{cases} Iter \le n, \\ \left| f\left(X_{k+1}^{Eye}\right) - f\left(X_k^{Object}\right) \right| \le \varepsilon, \end{cases}$$

where $Iter$ is the current number of iterations, n is the set maximum number of iterations, ε is the calculation accuracy control value of the objective function, and its value needs to be determined according to the specific calculation model, generally $\varepsilon \le 0.001$.

According to the above calculation process of the specular reflection algorithm, the optimization iteration steps of the specular reflection algorithm can be summarized, as shown in Fig. 10.

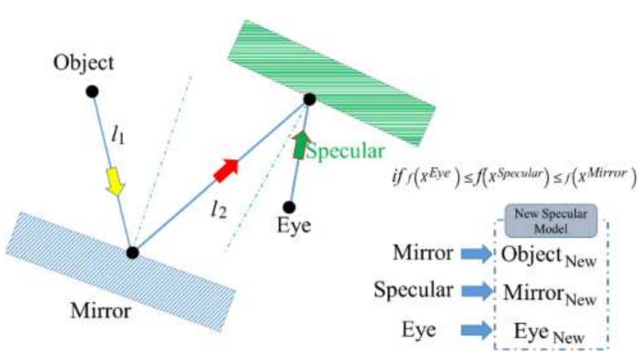

FIG. 8. New specular reflection model (condition 2).

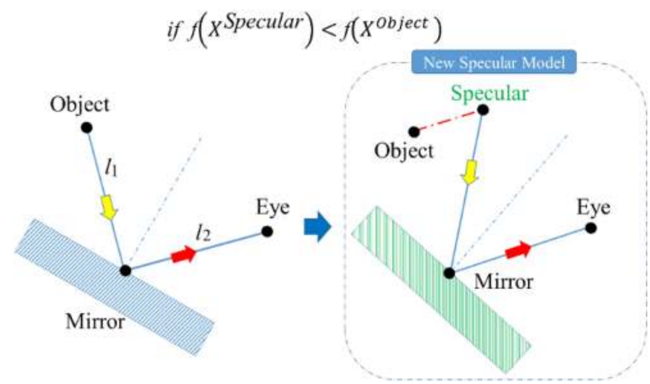

FIG. 9. New specular reflection model (condition 3).

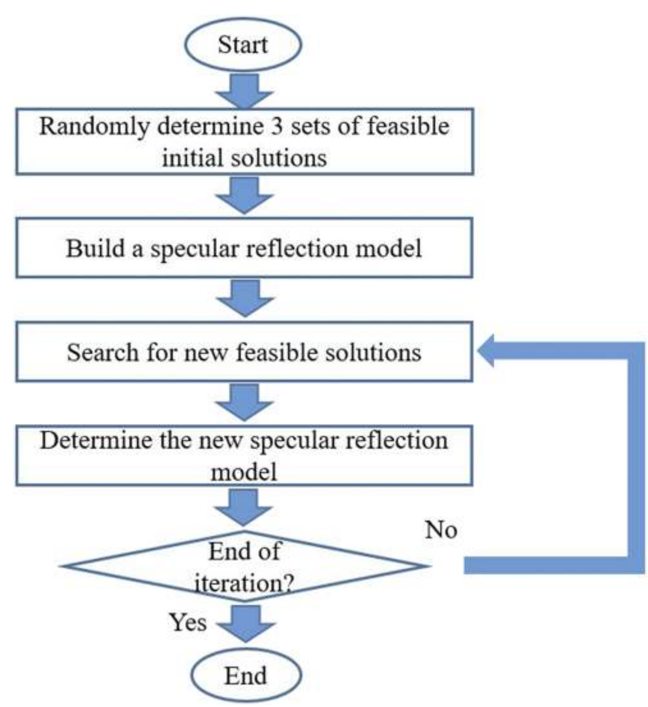

FIG. 10. Mirror reflection algorithm calculation process.

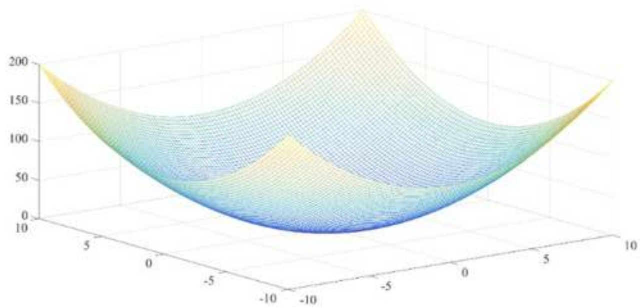

FIG. 11. 3D space surface of the test function.

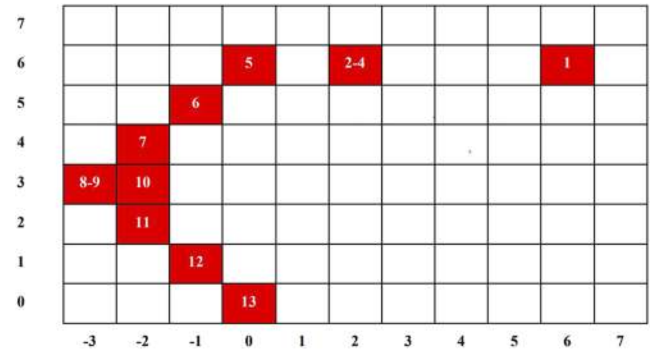

FIG. 13. X^{Eye} iteration path.

B. Numerical calculation analysis of specular reflection algorithm

To further illustrate the optimization method of specular reflection algorithm, the single peak test function as shown below is selected. The curve of the test function in three-dimensional space is shown in Fig. 11. According to the three-dimensional surface of the test function, this function has a unique global optimal solution, and the coordinate of the optimal solution is [0,0],

$$f(x) = \sum_{i=1}^{n} x_i^2.$$

The specular reflection algorithm is used to iteratively optimize the test function, and the optimal solution is obtained. The algorithm can obtain the global optimal solution $f(x_1, x_2) = 0$, after 28 iterative calculations, which proves that the specular reflection algorithm has high computational efficiency. The iterative convergence process of the objective function is shown in Fig. 12. Figure 12 contains three iteration process curves, namely, the uppermost iterative curve X^{Object}, the intermediate iterative curve X^{Mirror}, and the lowermost iterative curve X^{Eye}. The iteration curve of X^{Object} is not a strict descent but presents the law of fluctuation of the objective function. It is proved that the specular reflection algorithm can receive the optimal solution and the deteriorated solution in iteration, and the specular reflection model has diversity. The global search ability of the algorithm is improved. The curves of X^{Mirror} and X^{Eye} decrease strictly during the search process. This phenomenon shows that the objective function of the specular algorithm is strictly close to the better solution in the search process. The iterative process of the algorithm includes the process of obtaining the optimal solution and the receiving process of the non-optimal solution. The specular reflection algorithm searches for a solution at each iteration and converges after 28 iterations, and the calculation efficiency is high. The essence of the crane structure optimization design is a discrete optimization design problem. Discretize the design variables of the above-mentioned spherical test function. Design variables are taken as integers in the interval [−10,10]. This test function illustrates the characteristics of the specular reflection algorithm when dealing with discrete variable optimization problems. Figure 13 shows the search path of X^{Eye} in the entire feasible space. The specular reflection algorithm is used to optimize the test function after the design variables are discretized. The abscissa and ordinate in Fig. 13 are the values of the above spherical test function variables. The number in the red shadow is the count of iterations. As shown in Fig. 13, the shaded number is 6, and the coordinates (−1,5) indicate that in the sixth iteration, the search agent coordinates are (−1,5). The optimization results show that the optimal solution is obtained through 13 iterations in the whole optimization process. In one to seven iterations, the search speed is fast and it can quickly iterate to the optimal solution. In 8–13 iterations, the search direction always points to the global optimal solution and has the ability to jump out of the local optimal solution. Therefore, the algorithm has strong computational performance in discrete variable optimization problems. It can be used to solve the discrete variable optimization problem of the crane structure.

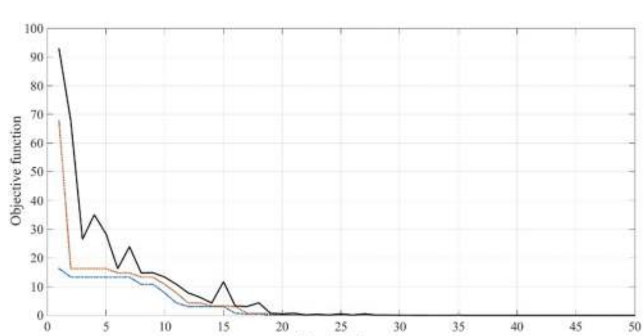

FIG. 12. Iteration curve.

IV. OPTIMIZED DESIGN OF CRANE STRUCTURE

The optimization design of the crane structure usually refers to the lightweight design of the structure. The lightweight design is a method of designing products only from the perspective of weight reduction. For most product designs, lightweight is a feasible method that can reduce the production costs of enterprises. However, the use of lightweight design methods cannot completely solve the problems that exist in the production process of enterprises, such as the efficient use of raw materials and the control of production costs. For the green design of the general bridge crane, this paper verifies the design of the general bridge crane from the perspective of the product lightweight design and steel cutting allowance minimization design. Two design models for minimizing the structure are established, and the specular reflection algorithm is used to optimize the crane structure design. The design results show that the specular reflection algorithm can be applied to the optimal design of crane structures, and the design results are reliable and effective.

A. Design variable

According to the above analysis, the design of the crane main girder structure meets the safety conditions, but the structural design redundancy is large, and the main beam can be further lightweight. In this section, the specular reflection algorithm is used to lightweight the main beam structure. The lightweight design of the crane girder structure needs to meet the requirements of structural strength, stiffness, and stability. The main girder of the bridge crane studied in this paper adopts the box girder structure, as shown in Figs. 1 and 2. The optimal design is realized by changing the section parameters. The section parameters of the main beam are shown in Fig. 2. The intelligent optimization algorithm is used to change some parameters to obtain the best objective function value (girder section area). Table II shows the design variables of the lightweight design of the crane main girder structure.

B. Restrictions

The design parameters need to meet the requirements of the dimensional constraints of the cross section and the structural design indices (strength, stiffness, and stability) of the crane. Table VIII shows the geometric constraints of the optimal design of the crane main beam structure. The constraint conditions of the structural design indicators are shown in Table III.

C. Objective function

For the two design goals of the lightweight design of the crane structure and minimum material cutting allowance, the optimized design model obtains the following two objective functions:

① Objective function 1

The lightweight design of the crane main girder structure can save steel consumption, reduce energy consumption, and reduce carbon emissions. The box girder of the main girder structure designed in this paper is welded by steel plates. The optimal design is achieved by changing the section design parameters.

The best combination of design parameters is obtained by using the optimization algorithm. The optimal design parameter combination of the main beam structure has the smallest cross-sectional area (structure quality). The objective function is a function represented by design variables and is mainly used to evaluate the pros and cons of the design results. The fluctuation of design variables affects the value of the objective function. Therefore, the value of the objective function is dependent on the design variables. In this paper, the objective function of the lightweight design of the bridge crane main girder structure can be defined as

$$f(x_1, x_2, x_3, x_4, x_5, x_6) = x_1(x_3 + x_4 + x_5 + 5x_1 + 30) + x_2(x_3 + x_4 + x_5 + 60) + 2x_6(x_3 + x_4).$$

② Objective function 2

The steel plate used by the crane for the welding of the main girder structure is cut from standard plates. The specifications of the plates are determined by the design parameters of the main girder section.

TABLE VIII. Summary of constraint conditions of the main girder structure of the bridge crane.

No.	Constraint formula	Constraint meaning
1	$x_i \geq 6, \frac{x_i}{2} \in Z, i = 1, 2, 3, 4$	Taking into account the steel plate models sold in the market, the thickness of the crane structural steel plate must be a positive integer greater than 6
2	$x_6 \leq 1800$	Taking into account the steel plate model and the limit size of the plate on the market, in order to ensure that there are no butt welds in the main girder web structure and reduce stress concentration, it should be ensured that the height of the web should be lower than the limited maximum plate width of the steel plate
3	$\frac{x_6}{x_5} \leq 3$	In order to meet the limiting conditions of the overall stability of the main girder, it is necessary to ensure that the aspect ratio of the main girder section is less than the limit value of 3
4	$x_1 \geq x_2 \geq x_3 \geq x_4$	In order to facilitate the determination of the objective function of the optimal design, the added limiting conditions
5	$x_6 \geq x_3 + x_4 + x_5 + 5x_1 + 30$	meet the actual processing requirements

In the production of enterprises, due to the lack of reasonable planning, excessive unnecessary material waste occurs in the processing process. As shown in Fig. 2, the thickness of the upper and lower flange plates of the main beam structure is 12 mm, the width of the upper and lower flange plates is 628 and 598 mm, and the sum of the width of the upper and lower flange plates is 1226 mm. The steel plate width specifications purchased by crane manufacturers are generally 1200, 1500, and 1800 mm. In this case, manufacturers usually use 1500 mm plates to process flange plates, and the width of the remaining steel plates after cutting is 274 mm. If the width of the upper flange plus the width of the lower flange is less than or equal to 1200 mm during design, the manufacturer's production cost can be reduced. The calculation of the function for the objective of cutting scrap with the main girder structure will be determined by the conditions shown in Table IX.

TABLE IX. Calculation of the objective function for the steel plate cutting optimization design.

Plate thickness condition	Board width condition 1	Board width condition 2	Processing waste
	$b_1+b_2+b_3+b_4 \le t_i$	···	$r_s=(t_i-b_{1-2-3-4})x_1$
		$b_1+b_2+b_3 \le t_i, b_4 \le t_j$	
		$b_1+b_3+b_4 \le t_i, b_2 \le t_j$	
		$b_2+b_3+b_4 \le t_i, b_1 \le t_j$	$r_s=(t_i+t_j-b_{1-2-3-4})x_1$
		$b_1+b_2 \le t_i, b_3+b_4 \le t_j$	
		$b_1+b_3 \le t_i, b_2+b_4 \le t_j$	
$x_1=x_2=x_3=x_4$	$b_1+b_2+b_3+b_4 > t_3$	$b_1+b_2 \le t_i, b_3 \le t_j, b_4 \le t_k$	
		$b_1+b_3 \le t_i, b_2 \le t_j, b_4 \le t_k$	
		$b_1+b_4 \le t_i, b_2 \le t_j, b_3 \le t_k$	$r_s=(t_i+t_j+t_k-b_{1-2-3-4})x_1$
		$b_2+b_3 \le t_i, b_1 \le t_j, b_4 \le t_k$	
		$b_3+b_4 \le t_i, b_1 \le t_j, b_2 \le t_k$	
		$b_1+b_2 \le t_i, b_3 \le t_j, b_4 \le t_m$	$r_s=(t_i+t_j+t_k+t_m-b_{1-2-3-4})x_1$
	$b_1+b_2+b_3 \le t_i$	···	$r_s=(t_i-b_{1-2-3})x_1+(t_m-b_4)x_4$
		$b_1+b_2 \le t_i, b_3 \le t_j$	
$x_1=x_2=x_3>x_4$	$b_1+b_2+b_3 > t_3$	$b_1+b_3 \le t_i, b_2 \le t_j$	$r_s=(t_i+t_j-b_{1-2-3})x_1+(t_m-b_4)x_4$
		$b_2+b_3 \le t_i, b_1 \le t_j$	
		$b_1 \le t_i, b_2 \le t_j, b_3 \le t_k$	$r_s=(t_i+t_j+t_k-b_{1-2-3})x_1+(t_m-b_4)x_4$
	$b_1=b_2 \le t_i, b_3=b_4 \le t_j$	···	$r_s=(t_i-b_{1-2})x_1+(t_j-b_{3-4})x_3$
$x_1=x_2>x_3=x_4$	$b_1=b_2 > t_3, b_3=b_4 \le t_k$	$b_1 \le t_i, b_3 \le t_j$	$r_s=(t_i+t_j-b_{1-2})x_1+(t_k-b_{3-4})x_3$
	$b_1=b_2 \le t_i, b_3=b_4 > t_3$	$b_3 \le t_k, b_4 \le t_m$	$r_s=(t_i-b_{1-2})x_1+(t_k+t_m-b_{3-4})x_3$
	$b_1=b_2 > t_3, b_3=b_4 > t_3$	$b_1 \le t_i b_2 \le t_j, b_3 \le t_k, b_4 \le t_m$	$r_s=(t_i+t_j-b_{1-2})x_1+(t_k+t_m-b_{3-4})x_3$
$x_1=x_2>x_3>x_4$	$b_1+b_2 \le t_i$	···	$r_s=(t_i-b_{1-2})x_1+(t_k-b_3)x_3+(t_m-b_4)x_4$
	$b_1+b_2 > t_3$	$b_1 \le t_i, b_2 \le t_j$	$r_s=(t_i+t_j-b_{1-2})x_1+(t_k-b_3)x_3+(t_m-b_4)x_4$
$x_1>x_2>x_3>x_4$	···	···	$r_s=(t_i-b_1)x_1+(t_j-b_2)x_2+(t_k-b_3)x_3+(t_m-b_4)x_4$
	$b_2+b_3 > t_3$	$b_2 \le t_j, b_3 \le t_k,$	
$x_1>x_2=x_3>x_4$	$b_2+b_3 \le t_i$	···	$r_s=(t_i-b_1)x_1+(t_j+t_k-b_{2-3})x_2+(t_m-b_4)x_4$
	$b_2+b_3+b_4 \le t_j$	···	$r_s=(t_i-b_1)x_1+(t_j-b_{2-3-4})x_2$
		$b_2+b_3 \le t_j, b_4 \le t_m$	$r_s=(t_i-b_1)x_1+(t_j-b_{2-3})x_2+(t_m-b_4)x_4$
$x_1>x_2=x_3=x_4$	$b_2+b_3+b_4 > t_3$	$b_3+b_4 \le t_k, b_2 \le t_j$	$r_s=(t_i-b_1)x_1+(t_j-b_{2-3})x_2+(t_m-b_4)x_4$
		$b_2 \le t_j, b_3 \le t_k, b_4 \le t_m,$	$r_s=(t_i-b_1)x_1+(t_j-b_2)x_2+(t_k-b_3)x_3+(t_m-b_4)x_4$
	$b_3+b_4 > t_3$	$b_3 \le t_k, b_4 \le t_m,$	
$x_1>x_2>x_3=x_4$	$b_3+b_4 \le t_k$	···	$r_s=(t_i-b_1)x_1+(t_j-b_2)x_2+(t_k-b_{3-4})x_3$

where x_1, x_2, x_3, x_4 are the thicknesses of the main girder structure [x_1 is the thickness of the upper flange plate, x_2 is the thickness of the lower flange plate, x_3 is the thickness of the main web, and x_4 is the thickness of the secondary web (in mm)], b_1, b_2, b_3, b_4 are the steel plate width parameters corresponding to the main girder structure plate thickness x_1–x_4 (in mm), t_1, t_2, t_3 are steel plate widths of specific specifications [$t_1 = 1200, t_2 = 1500, t_3 = 1800$ (in mm)], and i, j, k, m are variable subscripts $(i, j, k, m = 1, 2, 3)$

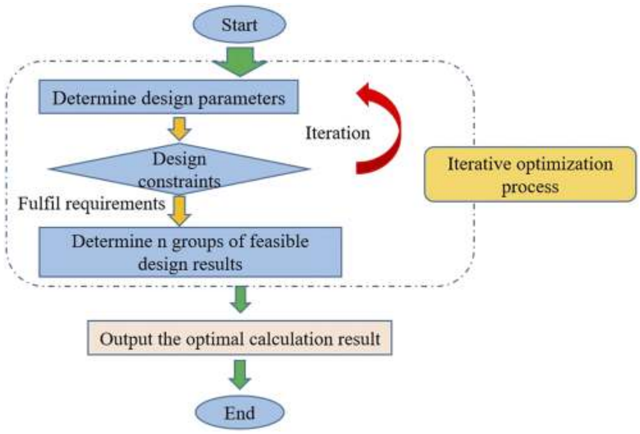

FIG. 14. Iterative process of crane structural design optimization.

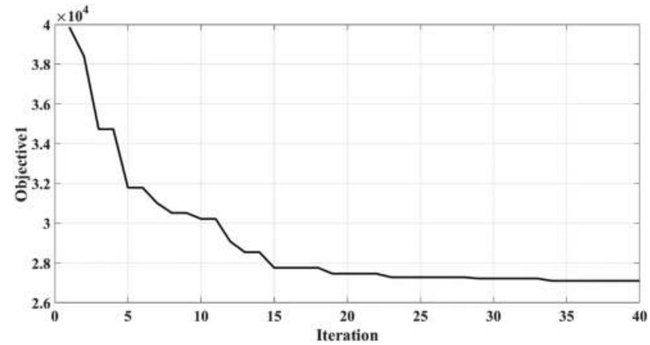

FIG. 15. Iterative curve of objective function 1.

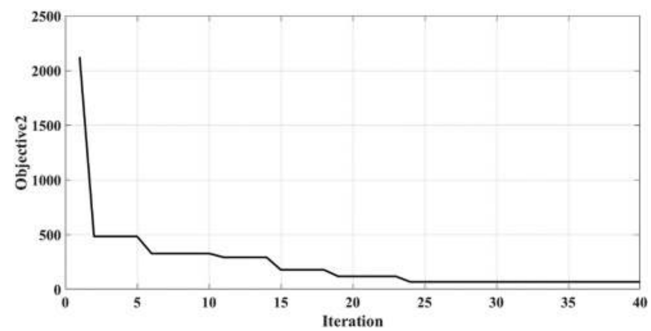

FIG. 16. Iterative curve of objective function 2.

D. Optimized design of crane structure

The two optimization problems presented completely different design results. Through the analysis, the different results are due to the different objective functions. The specular reflection algorithm is used to analyze and optimize the above two optimization models respectively. The calculation flow of structural optimization is shown in Fig. 14. The best combination of design parameters is obtained by the computer and specular reflection algorithm. The optimal combination of parameters meets the design requirements (constraints) and design index (objective function). The specular reflection algorithm is used to optimize the crane main girder structure based on two design goals. The design results are listed in Table X, and the results of the two optimization designs are quite different. This situation is caused by the different objectives of the two optimizations. Although the design with lightweight can obtain the minimum structure quality, it produces more processing waste, which leads to the waste of raw materials. For the optimization problem with the minimum processing waste as the objective, the weight of the structure obtained by the optimization is too large, which leads to the performance of the material not fully exerted.

Figure 15 shows the iterative curve of objective function ①. After 35 iterations, the optimal solution of objective function ① is obtained, and the cross-sectional area of the main girder is optimized to be 2.7×10^4 mm^2. In the iterative process, the iterative curve decreases steadily, the iterative speed is stable, and the global optimal solution is obtained directly. Figure 16 shows the iterative curve of objective function ②. After 25 iterations, the optimal solution of objective function ② is obtained, and the amount of cutting waste is reduced to 84 mm^2. In the early stage of iteration, the specular algorithm can converge to the global optimal solution at a faster speed. In the late stage of iteration, the image tends to be stable and fluctuates in a small range, so it is not easy to fall into the local optimal

TABLE X. Optimization calculation results of two design goals.

		Design variable						Objective function		Check result			
		x_1	x_2	x_3	x_4	x_5	x_6	Main girder section area	Cross-sectional area of processing waste	Maximum stress of Sec. 1	Maximum stress of Sec. 2	Maximum stress of Sec. 3	Maximum deformation of the main girder
No.	Design type	mm						mm^2	mm^2	MPa			mm
1	Original design	12	12	10	8	520	1250	37 212	7788	113.6367	95.1697	71.2292	22.0196
2	Lightweight design	6	6	6	6	580	1595	26 964	3636	130.9760	141.4609	123.6953	21.3275
3	Minimal processing waste	16	14	14	14	1060	1200	68 840	84	64.6870	64.3563	44.9337	11.3888

solution. Finally, the global optimal solution is obtained. In conclusion, for the optimization design of the crane girder structure, the specular algorithm has the ability of fast optimization and convergence. For any optimization model, the specular algorithm has the ability to obtain the optimal design results through a limited number of iterations. Through the analysis of the iterative curve, it can be seen that for the optimization calculation of the two models, the specular algorithm can obtain the convergence solution through a limited 40 iterations.

V. EVALUATION AND OPTIMIZATION OF GREEN DESIGN OF CRANE STRUCTURE

To evaluate the impact of the above two optimization models on the environment, the fuzzy comprehensive evaluation method is applied in this paper. The evaluation index is taken as the objective function of green design optimization of the crane structure. The specular reflection algorithm is used to design the new optimization model to obtain the structural design parameters with the optimal (green) index.

A. Fuzzy comprehensive evaluation on green design of crane structure

Fuzzy comprehensive evaluation is an analysis method based on fuzzy mathematics. This method can solve the problem that cannot be described by precise mathematical relations. The energy-saving evaluation process of crane main girder structure based on fuzzy comprehensive evaluation is as follows:

(1) Determine the set of factors:

For the research of this article, the factors to evaluate the green index of the crane structure include lightweight and material processing waste,

$$U = \{u_1, u_2\} = \{\text{Lightweightenergysaving, Materialprocessingwaste.}\}$$

(2) Determine the weight vector:

In this paper, according to the degree of influence of the two design indicators u_1 and u_2 on product energy saving, the following weight indicator values are determined:

$$A = \{a_1, a_2\} = \{0.9, 0.1\}.$$

(3) Determine the evaluation set:

Based on the results of partial limit design listed in Table X, this paper determines the evaluation matrix shown in Table XI,

$$V = \begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{bmatrix}.$$

(4) Calculate the evaluation result:

$$AV = \begin{bmatrix} 0.9 & 0.1 \end{bmatrix} \begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{bmatrix} = [0.9v_{11} + 0.1v_{21}, 0.9v_{12} + 0.1v_{22}].$$

$sum(AV)$ is a quantitative index for evaluating the energy saving of design parameters.

B. Fuzzy comprehensive optimization design of crane structure

The fuzzy comprehensive evaluation index of crane structure energy saving is $AV(1) = 0.9v_{11} + 0.1v_{21}$. Taking this parameter as the objective function, the green energy-saving optimization ($AV(1)$ minimization) design model of the crane structure is established. The specular reflection algorithm is used to perform the fuzzy optimization design on the optimization model. The results of the optimization design are shown in Table XII. The effect of blanks and processing waste during the manufacturing of the crane main girder structure is shown in Fig. 17. The iterative curve of the objective function with crane energy saving as the index is shown in Fig. 18.

According to the calculation results in Table XII, after the comprehensive analysis and optimization of the fuzzy evaluation

TABLE XI. Evaluation set determination.

Evaluation factor v_{11}	Evaluation factor v_{12}	Evaluation factor v_{21}	Evaluation factor v_{22}
$v_{11} = \frac{f1(x)-f1_{\min}}{f1_{\max}-f1_{\min}}$	$v_{12} = 1 - v_{11}$	$v_{21} = \frac{f2(x)-f2_{\min}}{f2_{\max}-f2_{\min}}$	$v_{22} = 1 - v_{21}$

where $f1(x)$ is the calculation result of objective function 1 caused by the design parameters,
$f1_{\min}$ is the minimum value of objective function 1 in Table X ($f1_{\min}$ = 26 964),
$f2(x)$ is the minimum value of objective function 1 in Table X ($f1_{\max}$ = 68 840),
$f2(x)$ is the calculation result of objective function 2 caused by the design parameters,
$f2_{\min}$ is the minimum value of objective function 2 in Table X ($f2_{\min}$ = 84),
and $f2_{\max}$ is the minimum value of objective function 2 in Table X ($f2_{\max}$ = 7788).

TABLE XII. Result of fuzzy comprehensive optimization for energy saving of the crane structure.

Design variable		Objective function value			Structure check results			
Symbol	Value	Objective function 1	Objective function 2	Objective function 3	Maximum normal stress of section 1	Maximum normal stress of section 2	Maximum normal stress of section 3	Maximum deformation of the main girder
mm		mm^2	mm^2	⋯	MPa			mm
x_1	8	27 152	2848	0.0399	133.6075	139.2945	117.4728	23.3058
x_2	8							
x_3	6							
x_4	6							
x_5	525							
x_6	1460							

method, the design indices of the crane structure have been improved compared with the original design. After fuzzy comprehensive optimization, the cross-sectional area of the main beam is reduced by 27.03% compared with the original design, and 1.77 tons of steel is saved. The purpose of lightweight is achieved. In addition, the processing waste is reduced by 63.43% compared with the original design, and about 0.8725 tons of processing waste is converted into usable steel. The output comparison of the crane main girder structure material and processing waste is shown in Fig. 17. The three rectangles on the left in the figure represent three blanking steel plates: steel plate 1, steel plate 2, and steel plate 3. The color part is the steel plate for welding the main beam, and the gray part is the cutting waste. Figure 17 shows that if the design of the main girder structure size is unreasonable, a large number of cutting waste will be produced, increasing the burden on the environment. Therefore, it is significant to reduce the weight of structure and the production of cutting waste by the fuzzy comprehensive optimization method.

According to the iterative curve of the objective function in Fig. 18, the fuzzy comprehensive evaluation method aiming at energy-saving evaluation of crane structure can be designed and analyzed by the intelligent optimization algorithm. The established optimization model is accurate and reliable. The specular reflection algorithm only needs 25 iterative calculations to obtain the optimal calculation results. The algorithm has a fast convergence speed and good calculation effect, which provides a very good design idea for

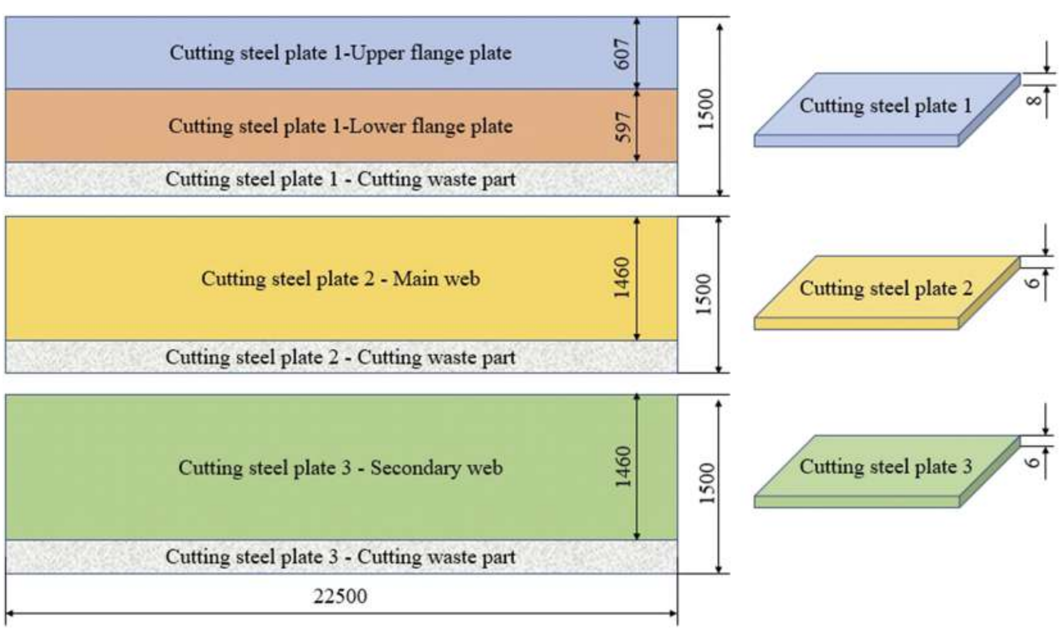

FIG. 17. Total amount of steel plates and processing waste of the main girder structure.

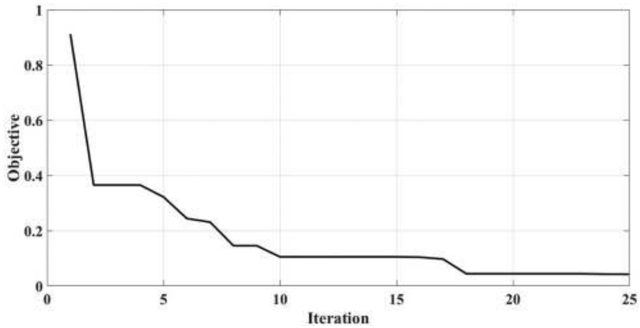

FIG. 18. Iterative curve of the objective function $AV(1)$.

the energy-saving design of the crane structure and the lightweight of the product.

VI. CONCLUSION

The failure to apply advanced design theories in the early design of the general bridge crane with a lifting weight of 20t and a span of 22.5 m results in the heavy weight of the crane structure and the waste of raw materials. The specular reflection algorithm is used in the optimization design process, and two optimization design schemes for the crane main girder structure are proposed. One aims at the lightweight structure, and the other is with minimum processing waste as the goal from the perspective of energy saving. The results prove that the specular reflection algorithm can be widely used in the optimization design of crane structures. Due to the singleness of the design goal, the results of the two design schemes can only meet either design goal. For the other indicator, the performance of schemes is poor. In order to comprehensively evaluate the crane structure design, a fuzzy comprehensive evaluation method is used to construct the objective function of crane main girder structure optimization with energy saving as the goal. The results show that the method proposed in the paper can quickly and accurately conduct the energy saving evaluation and optimization of main girders of cranes. Meanwhile, compared with the original design, the energy-saving effect of the method is greatly improved. The fuzzy comprehensive evaluation method proposed in this paper provides a new idea for green energy-saving design in the engineering field.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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