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Tong YIFEI
Tang ZHAOHUI
Ye WEI
Yang ZHEN

RESEARCH ON ENERGY-SAVING OPTIMIZATION DESIGN OF BRIDGE CRANE

BADANIA DOTYCZĄCE OPTYMALIZACJI ENERGOOSZCZĘDNOŚCI KONSTRUKCJI SUWNICY POMOSTOWEJ

Bridge crane is one of the most widely used cranes in our country, which is indispensable equipment for material conveying in the modern production. The security of bridge crane is always focused on when being used. The important indicators of crane performances include strength, stiffness, and crane weight, which mainly depend on the structure design of the bridge crane. So it is of importance to research on energy-saving optimization design by means of finite element analysis, ADMAS and Matlab. In this paper, the framework of energy-saving optimization is proposed. Secondly, taking 50 t – 31.5 m bridge crane as research object, its structure is described and the FE model of the bridge cranes is developed for the finite element analysis. Thirdly, shape optimal mathematical model of the crane is proposed for shape optimization as well as size optimal mathematical model for size optimization and topology optimal mathematical model for topology optimization. Besides, further comprehensive energy-saving optimizations are carried out as well as cross-section optimization. Finally, system-level energy-saving optimization design of bridge crane is further carried out with energy-saving transmission design results feedback to energy-saving optimization design of metal structure. The optimization results show that structural optimization design can reduce total mass of crane greatly by using the finite element analysis and optimization technology premised on the design requirements of cranes such as stiffness, strength and so on, thus energy-saving design can be achieved.

***Keywords**: Energy-saving design, Lightweight design, Shape optimization, Size optimization, Topology optimization, Bridge crane, HyperWorks.*

Suwnica pomostowa jest jednym z najczęściej używanych typów suwnic w Chinach i stanowi niezbędne wyposażenie do transportu materiałów w nowoczesnej produkcji. Kluczową kwestią dotyczącą obsługi suwnicy pomostowej jest zawsze bezpieczeństwo. Ważnymi wskaźnikami wydajności suwnicy są m.in. wytrzymałość, sztywność oraz ciężar suwnicy, które zależą głównie od konstrukcji suwnicy. Konieczne są zatem badania nad optymalizacją energooszczędności konstrukcji za pomocą analizy elementów skończonych, ADMAS oraz Matlab. W niniejszej pracy zaproponowano koncepcję optymalizacji energooszczędności. Po drugie, opisano budowę suwnicy pomostowej (50 t – 31.5 m) oraz opracowano model MES suwnicy do analizy metodą elementów skończonych. Po trzecie, przyjmując minimalną pojemność jako funkcję celu, wysokość i szerokość suwnicy jako zmienne projektowe, a naprężenie, energię odkształcenia, modalnych jako ograniczenia, ustalono optymalny model matematyczny kształtu żurawia dla celów optymalizacyjnego projektowania kształtu. Po czwarte, przyjmując minimalny udział objętościowy jako funkcję celu, a grubości płyt jako zmienne projektowe, ustalono optymalny model matematyczny rozmiarów do celów optymalizacyjnego projektowania rozmiarów. Po piąte, przyjmując minimalny udział objętościowy jako funkcję celu, a gęstości materiału każdego z elementów jako zmienne projektowe, ustalono optymalny model matematyczny topologii do celów optymalizacyjnego projektowania topologii. Wreszcie, wykonano multidyscyplinarny energooszczędny projekt optymalizacyjny systemu suwnicy pomostowej, a wyniki energooszczędnego projektowania układu napędu zostały wykorzystane jako informacja zwrotna przy energooszczędnym projektowaniu optymalizacyjnym konstrukcji metalowej. Wyniki optymalizacji pokazują, że optymalizacyjne projektowanie konstrukcji z wykorzystaniem analizy MES oraz technologii optymalizacji opartej na wymogach projektowych dla suwnic, takich jak sztywność, wytrzymałość itd., może znacznie obniżyć całkowitą masę dźwigu, a co za tym idzie zwiększyć jego energooszczędność.

***Słowa kluczowe**: Energooszczędna konstrukcja, lekka konstrukcja, multidyscyplinarna optymalizacja, suwnica pomostowa, HyperWorks.*

1. Introduction

Empirical design is often used for the structure design of bridge crane, which determines the design parameters of bridge crane and furthermore improve the performance. The traditional design method can't work out accurate performance data resulting in the safe coefficient of crane over the design requirements greatly, which leads to the waste of materials and energy consumption, etc [9].

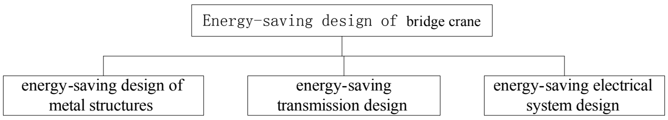
At present, simplified structure to reduce the weight and lightweight design based heuristic algorithm are usually adopted to achieve energy saving, most of which focus on single structural design improvement. With the rapid development of finite element analysis (FEA) technique [8, 10], the traditional design method is gradually replaced by finite element analysis and design. There is quite a lot of finite element analysis software, such as: ANSYS, ABAQUS, and HyperWorks, etc [5, 11]. However, purely from structural design to reduce the weight of the crane has been very limited, and blindly to reduce the weight would be a security risk. On the other hand, crane is a complex system composed of many subsystems, among which there exist weak or strong coupling relationship. Thus, Crane energy-saving design is a multi-disciplinary coupling engineering problem involving structural design, mechanical transmission and electrical control, which is not a simple superposition and permutations of various disciplines design. Therefore it is of urgent need from multidisciplinary point of view of structure, mechanical transmission and electrical control to study the system-level energy-saving design of crane.

The present work was carried out in order to obtain simulation data of the bridge crane. In the next section, the framework of energy-saving optimization design is proposed. In Section 3, FE model of double girder crane is developed using commercial program HyperWorks and the loading and the results of finite element analysis are given and discussed. Shape, size and topology optimization are further carried out as well as comprehensive optimization and the results of structural optimization are analyzed. In Section 4, oyerall energy-saving optimization design of bridge crane is further carried out with energy-saving transmission design results feedback to energy-saving optimization design of metal structure. Finally, research conclusions are summarized.

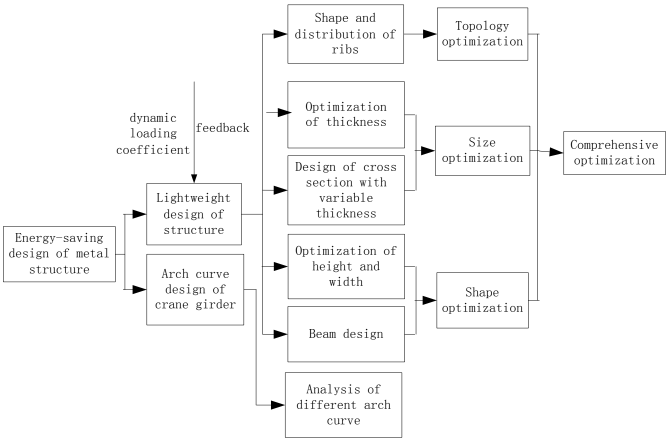
2. Energy-saving optimization design framework

The presented research on crane energy-saving design technology includes three parts respectively: energy-saving design of metal structures, energy-saving transmission design and energy-saving electrical system design. Energy-saving design of metal structure involves structural lightweight design and arch curve design of beam, energy-saving transmission system design involves dynamic loading, transmission efficiency and components lightweight and energy-saving electric system design involves power loss.

In addition, optimal design of lifting findings dynamic loading and components lightweight are feedback to structure lightweight design for further design optimization. Also, arch curve can reduce climbing energy consumption, thereby reducing motor power losses. The arch curve optimization results need feedback for electrical energy-saving. The optimization design can be illustrated as shown in Fig.1.

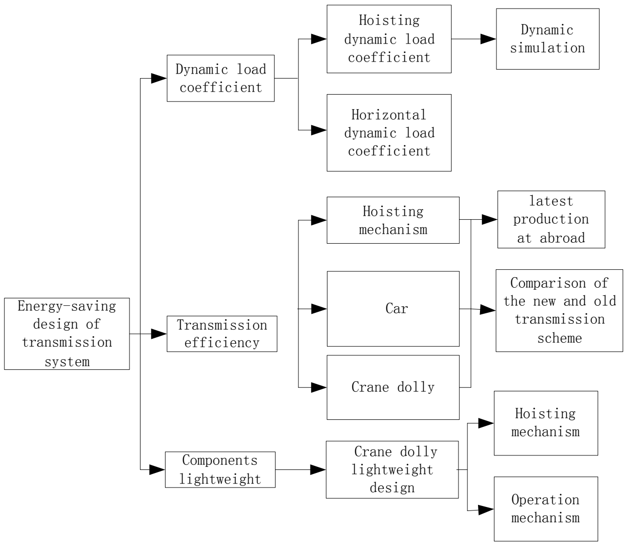


a) overall framework of energy-saving design

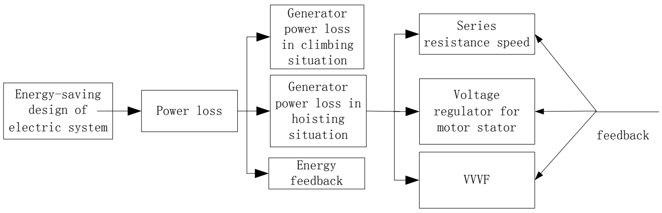


b) energy-saving design of metal structure

Fig. 1a-b. Energy-saving optimization design framework



c) energy-saving design of transmission design



d) energy-saving design of electrical system design

Fig. 1c-d. Energy-saving optimization design framework

3. Energy-saving optimization design of metal structure of bridge crane

3.1. Development of FE model of double girder crane

Take a bridge crane used in a practical project as the research object, which is a 50t-31.5m double girder crane whose material parameter and usage are as follows:

- material: ordinary carbon steel Q345;
- Length of the crane( ): 31.5m;
- maximum lifting height: 12m;
- hoisting speed: 7.8 m/min;
- moving speed of the car: 38.5 m/min;
- moving speed of the cart: 87.3 m/min.

And according to the GBT 3811-2008 “Crane design standard”,the working-level of car is M5, and the working-level of cart is M6 [1].

3.2. Geometric modeling of double girder crane

According to the engineering drawing, geometric model of the bridge crane is established by PRO/E, whose structure components include the up and down plates of end girders, the side plates of end

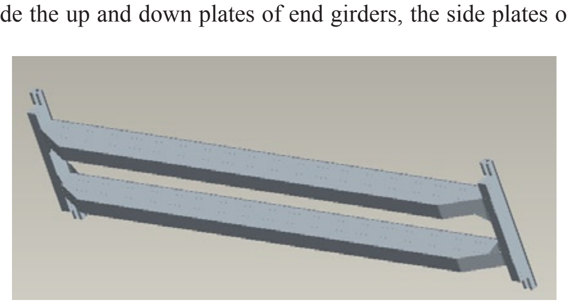


Fig. 2. Geometric model of double girder crane

girders, up and down plates of main girders, the side plates of main girders, multiple belly boards, feet frame and various connection boards. The simplified geometric model is shown as Fig. 2.

3.3. Model Processing

Import the geometric model of bridge crane into HyperMesh, and clear it. Owing to that each plate is thin, partition the plates with shell elements for finite element simulation analysis. The shell elements should be created on the middle surface of the geometry. A group of middle surfaces should be constructed by using "Midsurface" panel. The imported model contains some connectivity error or some other defects, so the operations as follows should be carried out after importing file model:

1) Delete the unsheared surfaces.
2) Fill the gaps (repair the missed surfaces).
3) Set the tolerance values of geometric clean- ing.
4) Combine the red free edges with "Equivalence".
5) Delete the repeated surfaces.

3.4. Mesh partitioning of double girder crane

Welds connections between each board are taken place of the rigid connections and mesh elements are created on extraction midsurface [2]. The calculation capacity and calculation efficiency must be considered when mesh partitioning. Finer the elements meshed are, more accordant the partitioned model is with the actual condition, while computing time and memory usage will be increased largely. After taking all the above factors into account synthetically, set the element size as 50mm×50mm for finite element analysis. The Spot-welds are used to simulate the connections between the end and main girders [7].

Due to that the bridge crane structure is symmetrical, take half of the model as research object in order to reduce the computing time and memory usage. The FE model of bridge cranes is shown in Fig. 3.

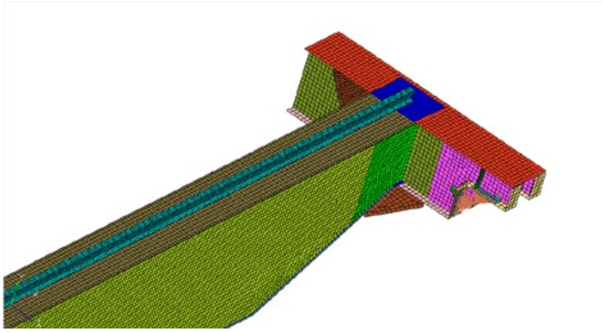


Fig. 3. Finite element model

3.5. Loading and static analysis

Both end girders and main girders are processed as simply supported beams [12, 13, 14]. Loading is illustrated as in Fig.4.

Constraint loadings of the crane are described as follows:

The movement in x, y, z directions and the rotation in z direction of position 1 are restrained;

The movement in y, z direction and the rotation in z direction of position 4 are restrained;

The movement in z direction and the rotation in x, y direction of position 2, 3 are restrained because of the symmetry.

The loadings on both of the main girders are as follows:

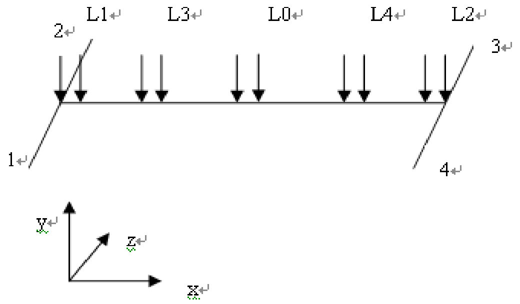


Fig. 4. Loadings illustration

- Rated hoisting loading : = 50 t
- The car mass is 15.765 t
- Self-vibration load factor = 1.1
- Lifting dymmic load factor = 1.14
- Horizontal inertial force of Crane as volume force: acceleration is 0.32m/s^2.
- Cart gravity as volume force

L0, L1, L2, L3, L4 denote the loadings on different positions of one main girder respectively called five work conditions, and the magnitude of the loadings (L0, L1, L2, L3, L4) is 322.2485 KN. Five work conditions are calculated in finite analysis as Table 1.

Table 1. Five work conditions description

Work conditions	Cart gravity (m/s^2)	Cart mass (t)	Self-vibration factor	Horizontal inertial force of crane (m/s^2)	Rotated loading (t)	Lifting move load factor	Load position
1	9.8	15.765	1.1	0.32	50	1.14	Middle of the beam
2	9.8	15.765	1.1	0.32	50	1.14	Left end of the beam
3	9.8	15.765	1.1	0.32	50	1.14	Right end of the beam
4	9.8	15.765	1.1	0.32	50	1.14	Left 1/4 of the beam
5	9.8	15.765	1.1	0.32	50	1.14	Right 1/4 of the beam

According to requirements of the crane design in GBT 3811-2008 "Crane Design" combined with actual usage, requirements for the stiffness of the crane girder are as follows:

$$f \leq \frac{1}{800} s$$

Where, f is the deflection displacement, S is the span of the crane [4].

And requirements for the stress of the crane girder are as follows:

- Material: Q345;
- Yield stress ;
- Allowable stress defined by engineering design.

After Loading on different locations of the main girder, the results of finite element analysis are shown in Fig. 5 and Fig. 6.

Analyzing and comparing different conditions of loads to obtain the conclusions that when loading on the middle of the main girder, the maximum displacement of 40.3 mm appears on the middle of the main girder, and the maximum stress of 91.6 MPa occurs on the middle of the main girders. According to the results of FEA, the total mass of the initial model is 18.9 t.

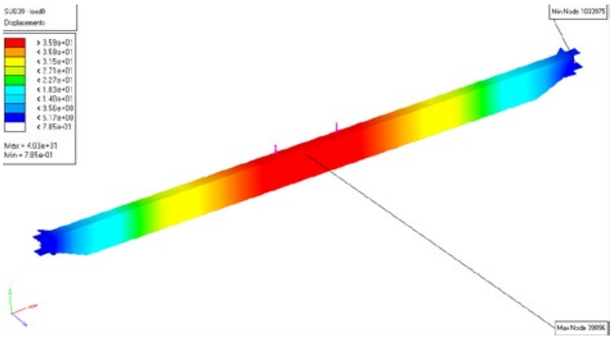


Fig. 5. Displacement cloud

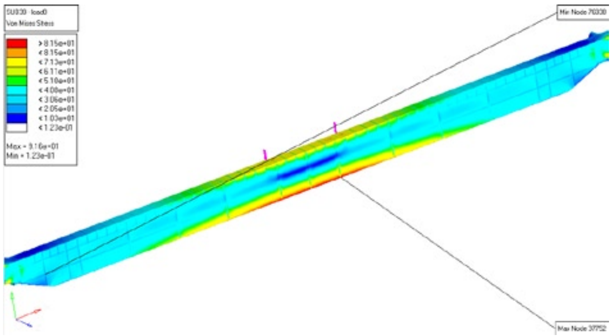


Fig. 6. Stress cloud

3.6. Structural optimization of double girder crane

3.6.1. Shape optimization

The shape optimal mathematical model is proposed as follows which takes the minimum volume as objective function, the height and width of the crane as design variables, and the scopes of stress, strain energy, modal as constraints:

Min $V'(X) = V'(Height', Width')$

Design variables:
$$-5 \le \text{Height}' \le 20$$
$$-5 \le \text{Width}' \le 20$$

S.T.
$$C_j = \frac{1}{2} u_j^T f_j \le 1.1\times 10^7 J \qquad j = 1,\cdots,5$$
$$Ku = f$$
$$\sigma \le 150MPa$$
$$F \ge 3$$

Where, $V'(X)$ denotes the volume fraction; C_j denotes the total strain energy of the crane under the j^th^ load; K denotes the stiffness matrix of the system; f denotes the load; u denotes the node displacement vector under the load f; σ denotes the stress; F denotes the natural frequency. Objective function $V'(X)$, constraint function C_j and σ can be obtained from structural response of the finite element analysis.

Use optistruct solver to optimize the girder by selecting morph optimization tool, the optimization results of the main girder are shown as follows:

Volume = 2.2E+09 mm^3, Mass = 17.36 t

Height′ = 1.03, Width′ = 1.74

After shape optimization:

Height = 1724 mm − 1.03×50 mm = 1672.5 mm

Width = 600 mm − 1.74×50mm = 513mm

Height/Width = 1672.5/513 = 3.26

By analyzing the results of finite element analysis, the structure performance (including strength, stiffness and modal) after topology optimization meet the requirements of crane design specifications greatly, which are shown in Fig.7 and Fig. 8.

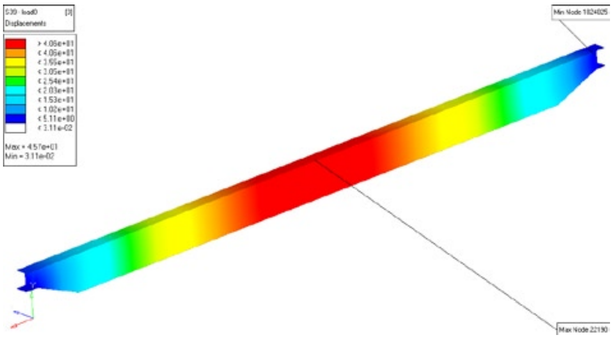


Fig.7. Displacement cloud-Shape optimization

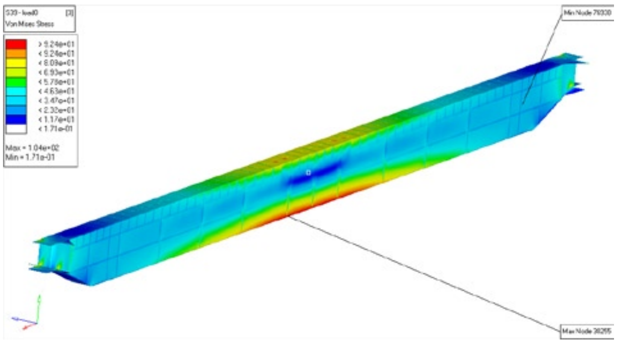


Fig. 8. Stress cloud-Shape optimization

Analyzing and comparing different conditions of loads to obtain the conclusions that when loading on the middle of the main girder, the maximum displacement of 45.7 mm appears on the middle of the main girder, and the maximum stress of 98.6 MPa occurs on the middle of the main girders. The total mass of the model after shape optimization is 17.4t, which has reduced by 7.9%.

Compare the maximum displacement and maximum stress before and after topology optimization, the result is given as in Table 2.

Table 2. Comparison of the stress and displacement

Load step	Before		Afer	
	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
L0	91.6	40.3	104	45.7
L1/L2	80.2		87.2	
L3/L4	74.5		74.4	

The above analysis results show that structure performance of the various plates, some materials of which have been reasonably removed, meets the design requirements as well. Meanwhile, the total mass of structure is 17.4 t, which has reduced by 1.5 t.

3.6.2. Size optimization

Furth optimizing of the structure after shape optimization was carried out in our research. Taking the minimum volume as the objective function, the thicknesses of the plates as the design variables, the scopes of the stress, strain energy and modal as constraints, the size optimal mathematical model is proposed as follows:

$$\text{Min} \quad V(X) = V(x_1, x_2, \cdots, x_{18})$$

$$\text{S.T.} \quad \begin{aligned} & C_j = \frac{1}{2} u_j{}^T f_j \le 1.1 \times 10^7 J \qquad j = 1, \cdots, 5 \\ & Ku = f \\ & \sigma \le 150MPa \\ & F \ge 3 \end{aligned}$$

Where denote the thicknesses of plates, denotes the total volume of the crane, the rest of variable parameters denotes as the above. Use the Optistruct solver to optimize girders by size optimization tool. The optimization results of the thicknesses of the plates are shown in the Table 3.

Table 3. Comparison the thicknesses before and after optimization

Main optimal size	Before (mm)	After (mm)
Upper plates	24	20.9
Upper plates 1	18	10.3
Upper plates 2	24	21.1
Small Ribbed plates	8	10
Big Ribbed plates	8	5.1
Junction plate	40	27.7

By analyzing the results of size optimization, the structure performance (including strength, stiffness and modal) after topology optimization meet the requirements of crane design specifications greatly. The results of finite element analysis after size optimization are shown in Fig. 9 and Fig. 10.

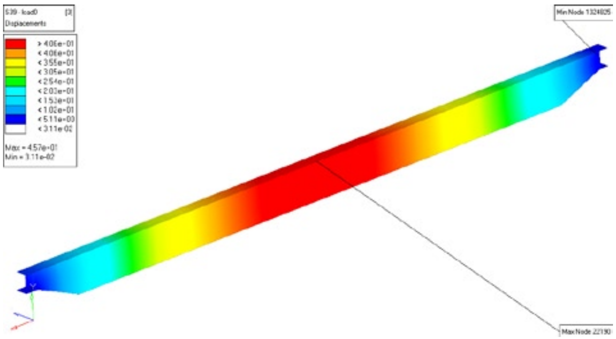


Fig. 9. Displacement cloud- Size optimization

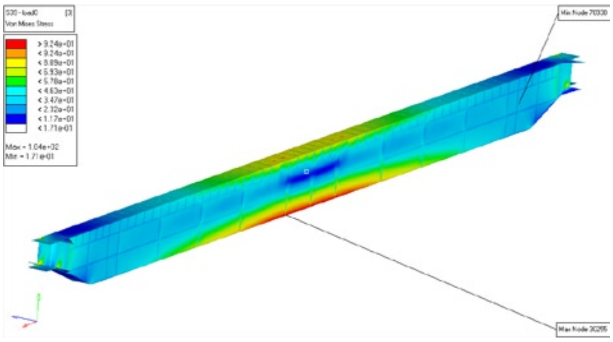


Fig. 10. Stress cloud- Size optimization

The maximum displacement of 46.4 mm appears on the middle of the main girder, and the maximum stress of 135 MPa occurs on the end of the main girders. The total mass of the model after size optimization is 17.6 t, which has reduced by 6.9%.

The comparison of initial model and final model is shown in the Table 4.

Table 4. Comparing the stress and displacement

Load step	Initial model		Final model	
	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
L0	91.6	40.3	135	46.4
L1/L2	80.2		132	
L3/L4	74.5		126	

From the above analysis results, it can be found easily that the structure performance after shape and size optimization meets the requirements of crane design specifications greatly. Moreover, after size optimization, the total mass of the main girder changes into 17.6 t which has been reduced by 1.3 t.

3.6.3. Topology optimization

Furth optimizing of the structure after shape and size optimization was carried out. The topology optimal mathematical model is proposed as follows which takes the minimum volume fraction as objective function, the material density of each element as design variables, and the scopes of stress, strain energy, modal as constraints:

$$\text{Min} \quad X = x_1, x_2, \cdots, x_n$$

$$\text{S.T.} \quad \begin{aligned} & C_j = \frac{1}{2} u_j{}^T f_j \le 1.1 \times 10^7 J \qquad j = 1, \cdots, 5 \\ & Ku = f \\ & \sigma \le 150MPa \\ & F \ge 3 \end{aligned}$$

Where, $X = x_1, x_2, \cdots, x_n$ denotes the material density of each element; and the rest of variable parameters denotes as the above.

Use Optistruct solver to optimize the girder by selecting Topology Optimization tool, the optimization results of the main girder are shown in Fig. 11.

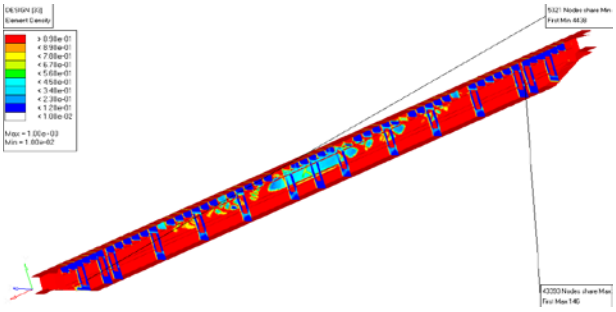


Fig. 11. Density graph-Topology optimization

By analyzing the results of topology optimization, the structure performance (including strength, stiffness and modal) after topology optimization meet the requirements of crane design specifications greatly. The results of finite element analysis after topology optimization are shown in Fig. 12 and Fig. 13.

Analyzing and comparing different conditions of loads to obtain the conclusions that when loading on the middle of the main girder, the maximum displacement of 39.8 mm appears on the middle of the main girder, and the maximum stress of 116 MPa occurs on the end of the main girders. The total mass of the model after topology optimization is 17.0 t, which has reduced by 10.05%.

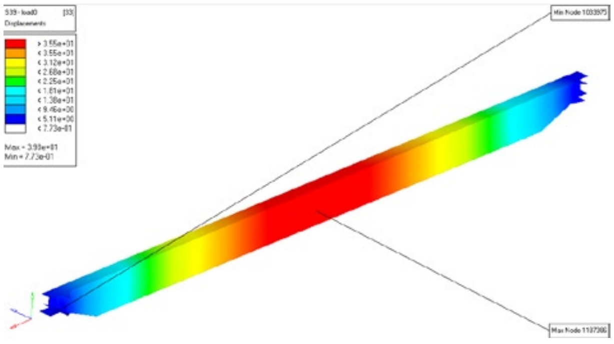


Fig. 12. Displacement cloud – Topology optimization

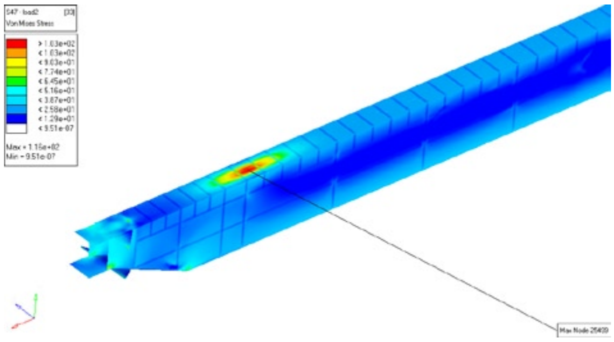


Fig. 13. Stress cloud – Topology optimization

Compare the maximum displacement and maximum stress before and after topology optimization, the result is given as in Table5.

Table 5. Comparison of the stress and displacement

Load step	Before		Afer	
	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
L0	91.6	40.3	88.9	39.8
L1/L2	80.2		109	
L3/L4	74.5		116	

The above analysis results show that structure performance of the various plates, some materials of which have been reasonably removed, meets the design requirements as well. Meanwhile, the total mass of structure is 17.0 t, which has reduced by 1.9 t.

3.7. Comprehensive "shape+size" optimization

The comprehensive optimization means to carry out size optimization for the crane model obtained after shape optimization. That is to remodelling according to shape optimization result and make size optimization. The optimization variables, constraint function and objective function are the same as mathematical optimization model of size optimization. The optimization results are shown as follows:

Volume = 2.04E+09 mm^3 Mass = 16.1 t

Table 6. Comparison the thicknesses before and after optimization

Main optimal size	Before (mm)	After (mm)
Upper plates	24	21.5
Upper plates 1	18	8.7
Upper plates 2	6	6
Small Ribbed plates	6	6
Big Ribbed plates	8	5.2
Junction plate	8	3

The optimization results of the thicknesses of the plates are shown in the Table 6.

By analyzing the results of size optimization, the structure performance (including strength, stiffness and modal) after topology optimization meet the requirements of crane design specifications greatly. The results of finite element analysis after size optimization are shown in Fig. 14 and Fig. 15.

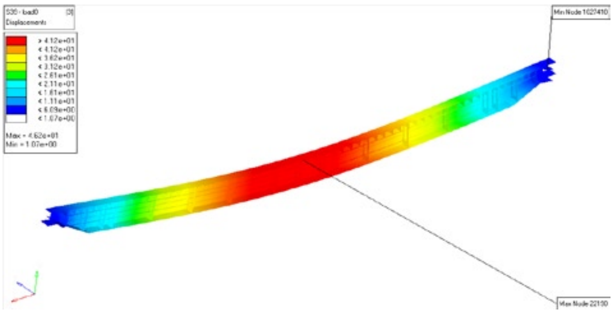


Fig. 14. Displacement cloud – "shape+size" optimization

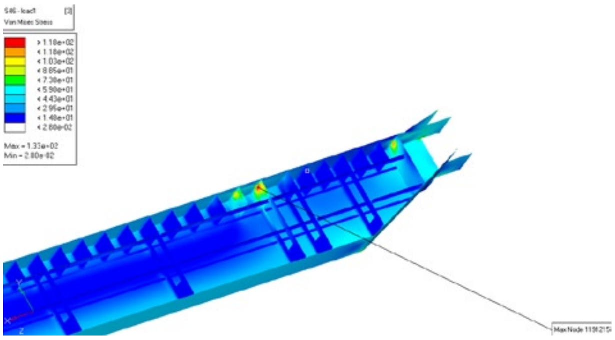


Fig. 15. Stress cloud – "shape+size" optimization

The comparison of initial model and final model is shown in the Table 7.

Table 7. Comparing the stress and displacement

Load step	Initial model		Final model	
	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
L0	91.6	40.3	125	46.2
L1/L2	80.2		128	
L3/L4	74.5		133	

From the above analysis results, it can be found easily that the structure performance after shape and size optimization meets the requirements of crane design specifications greatly. Moreover, after size optimization, the total mass of the main girder changes into 16.1 t which has been reduced by 14.8%.

3.8. Comprehensive "shape+size+topology" optimization

The comprehensive optimization means to carry out topology optimization for the crane model obtained after "shape+size" optimization. That is to remodelling according to"shape+size" optimization result and make topology optimization. The optimization variables, constraint function and objective function are the same as mathematical optimization model of topology optimization. The optimization results are shown as follows:

Mass=15.8t.

The optimization results of the main girder are shown in Fig.16.

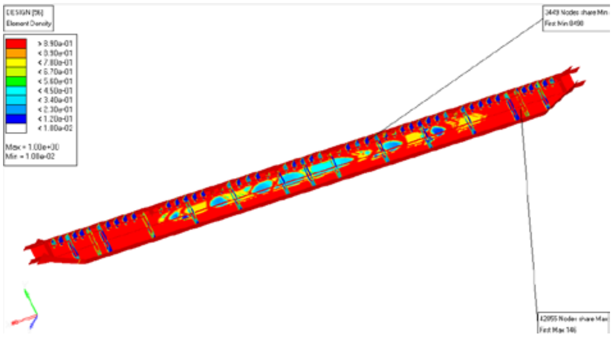


Fig. 16. Density graph – "shape+size+topology" optimization

By analyzing the results of topology optimization, the structure performance (including strength, stiffness and modal) after optimization meet the requirements of crane design specifications greatly. The results of finite element analysis after topology optimization are shown in Fig. 17 and Fig. 18:

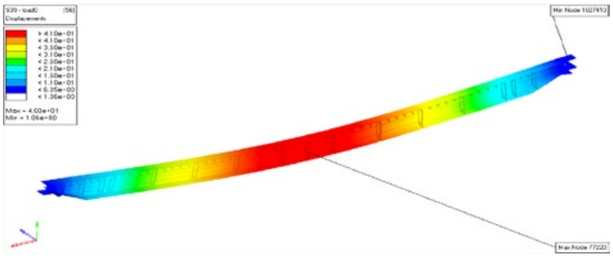


Fig. 17. Displacement cloud – "shape+size+topology" optimization

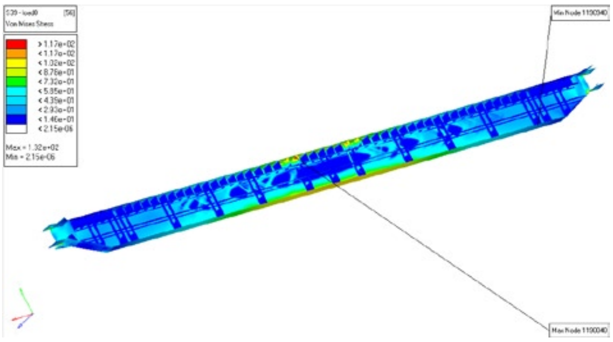


Fig. 18. Stress cloud – "shape+size+topology" optimization

Compare the maximum displacement and maximum stress before and after topology optimization, the result is given as in Table 8.

Table 8. Comparison of the stress and displacement

Load step	Before		Afer	
	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
L0	91.6	40.3	132	46
L1/L2	80.2		132	
L3/L4	74.5		128	

The above analysis results show that structure performance of the various plates, some materials of which have been reasonably removed, meets the design requirements as well. Meanwhile, the total mass of structure is 15.5 t, which has reduced by 18%.

3.9. Cross-section optimization

The optimization means to carry out size optimization for plate thickness of each plate of main girder, so as to realize Cross-section optimization design of main girder.

Table 9. Design variables and their range

No	Design variable	Initial value (mm)	Lower range value (mm)	Higher range value (mm)
1	Up1 (up plates)	24	1	50
2	Up2 (up plates)	24	1	50
3	Up3 (up plates)	24	1	50
4	Down1 (under plates 2)	24	1	50
5	Down2 (under plates 2)	24	1	50
6	Down3 (under plates 2)	24	1	50
7	Down18 (under plates 1)	18	1	30
8	Ribbed plates1	8	1	10
9	Ribbed plates2	8	1	10
10	Ribbed slab	8	1	10
11	Left1 (sternum)	6	4	15
12	Left2 (sternum)	6		15
13	Left3 (sternum)	6	4	15
14	Right1 (sternum)	6	4	15
15	Right2 (sternum)	6	4	15
16	Right3 (sternum)	6	4	15

Use the Optistruct solver to optimize girders by size optimization tool, the optimization results of the main girder are shown as follows:

Volume= 1.97E+09 mm^3, Mass = 15.5t

The optimization variable values are shown in the Table 10.

Table 10. Comparison the thicknesses before and after optimization

No	Design variable	Before (mm)	After (mm)
1	Up1 (up plates)	24	1
2	Up2 (up plates)	24	1
3	Up3 (up plates)	24	1
4	Down1 (under plates 2)	24	1
5	Down2 (under plates 2)	24	1
6	Down3 (under plates 2)	24	1
7	Down18 (under plates 1)	18	1
8	Ribbed plates1	8	1
9	Ribbed plates2	8	1
10	Ribbed slab	8	1
11	Left1 (sternum)	6	4
12	Left2 (sternum)	6	
13	Left3 (sternum)	6	4
14	Right1 (sternum)	6	4
15	Right2 (sternum)	6	4
16	Right3 (sternum)	6	4

By analyzing the results of finite element analysis, the structure performance (including strength, stiffness and modal) after topology optimization meet the requirements of crane design specifications greatly, which are shown in Fig. 19 and Fig. 20.

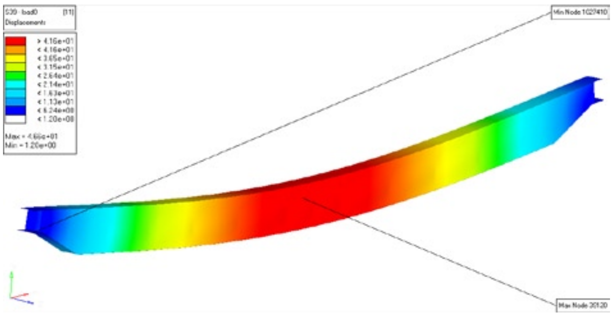


Fig. 19. Displacement cloud – Cross-section optimization

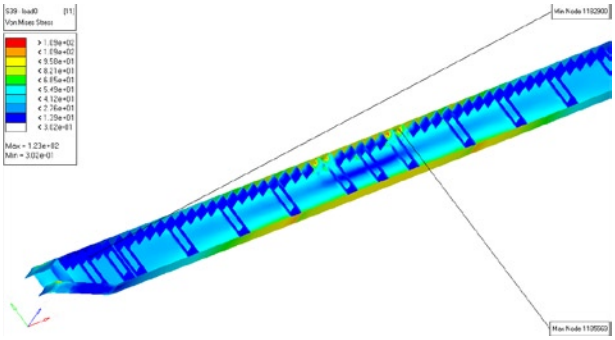


Fig. 20. Stress cloud – Cross-section optimization

Analyzing and comparing different conditions of loads to obtain the conclusions that when loading on the middle of the main girder, the maximum displacement of 46.6 mm appears on the middle of the main girder, and the maximum stress of 123 MPa occurs on the middle of the main girders. The total mass of the model after shape optimization is 15.5 t, which has reduced by 18%.

Compare the maximum displacement and maximum stress before and after topology optimization, the result is given as in Table 11.

Table 11. Comparison of the stress and displacement

Load step	Before		Afer	
	Stress (MPa)	Displacement (mm)	Stress (MPa)	Displacement (mm)
L0	91.6	40.3	123	46.6
L1/L2	80.2		108	
L3/L4	74.5		110	

The above analysis results show that structure performance of the various plates, some materials of which have been reasonably removed, meets the design requirements as well. Meanwhile, the total mass of structure is 15.5 t, which has reduced by 3.4 t.

3.10. Overall stability analysis of main girder

According to the requirements of "the crane design manual" for box section structure, "when aspect ratio (height/width) denoted by h/b≤3 or 3<h/b≤6 & $\frac{l}{b} \le 95\frac{235}{\sigma_s}$, the lateral buckling stability of the flexural components don't need verify."

In our research, the results are as follows:

Before optimization: h=1724 mm, b=600 mm, h/b=2.87, so h/ b≤3,

After optimization: h=1742 mm, b=540 mm, h/b=3.19, and l=31500 mm, l/b=58.3, σ_s =253 MPa. So 3<h/b≤6 & $\frac{l}{b} \le 95\frac{235}{\sigma_s}$.

Therefore, lateral buckling stability conforms to the design requirements.

4. System-level energy-saving optimization design of bridge crane

Energy-saving transmission design is researched by our research group in dynamic simulation and speed regulation of hoisting mechanism as well as optimization and innovation of transmission mechanism scheme reported in literature [13, 14]. Thus, self-vibration load factor in Section 3.4 is reduced from 1.14 to 1.11 under VVVF and the car mass in Section 3.4 is reduced from15.765 t to 14.4 t. System-level multidisciplinary energy-saving optimization design of bridge crane can be further carried out with energy-saving transmission design results feedback to energy-saving optimization design of metal structure. By repeating the above modelling and analysis in Section 3, the system-level multidisciplinary energy-saving optimization results are shown in Table 12.

Table 12. System-level energy-saving optimization results

Optimization method	Mass after optimizaton (t)	Percentage decrease
	18.9	
Shape optimization	17.1	9.52%
Size optimization	17.3	8.46%
Topology optimization	16.9	10.58%
"Shape+size" optimization	15.6	17.46%
"Shape+size+topology" optimization	15.5	17.99%
Cross-section optimization	14.9	21.16%

5. Conclusions

The framework of energy-saving optimization design of bridge crane is proposed. And the structure optimization design of bridge crane by using finite element analysis technology is discussed in this paper in detail. This research seeks to get more reasonable, lightweight and energy-saving structure on the basis of insuring the performances of crane, and to provide the design reference for bridge crane. The main results of this research can be concluded as follows:

1. The results of finite element analysis show that the concentrated stress occurs on the middle of main girders under full load.
2. For the cranes which meet the design requirements, shape optimization is researched. The total mass of the structure after shape optimization changes into 17.4 t /17.1 t (optimization design of metal structure/system-level energy-saving optimization) and it is reduced by 1.5 t /1.8 t compared with the initial model.
3. Size optimization is researched after shape optimization. The total mass of the structure after size optimization changes into 17.6 t/17.3 t and it is reduced by1.3 t/1.6.
4. Topology optimization based on density methodology is used after shape and size optimization. The total mass of the structure after topology optimization changes into 17.0 t/16.9 t and it is reduced by 1.9 t/2.0 t compared with the initial model.
5. The total mass of the structure after "shape+size" optimization changes into 16.1 t/15.6 t and it is reduced by 2.8 t/3.3 t compared with the initial model.

6. The total mass of the structure after "shape+size+topology" optimization changes into 15.5 t/15.5 t and it is reduced by 3.4 t/3.4 t compared with the initial model.
7. The total mass of the structure after cross-section optimization changes into 15.5 t/14.9 t and it is reduced by 3.4 t/4.0 t compared with the initial model.

Finite element structure optimization technique not only can assure stiffness, strength and other performances requirements of the crane, but also can greatly reduce the use of materials by lightweight design.

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Prof. Tong YIFEI
Researcher Tang ZHAOHUI M.E. candidate
Researcher Ye WEI M.E. candidate
Researcher Yang ZHEN M.E.
Nanjing University of Science and Technology, School of Mechanical Engineering 402, 210094 Nanjing, People's Republic of China
E-mails: tyf51129@yahoo.com.cn, 453651434 @qq.com, 837288965@qq.com gaochunyangzhen@163.com