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Structural Topology Optimization of Cantilever Crane Boom Based on Equivalent Moving Load Method

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Abstract. As a key structure in the process of lifting heavy objects by cantilever cranes, the boom is of great significance. When the cantilever crane carries heavy objects, the load on the boom is a typical moving load. The traditional structural optimization method cannot fully consider the influence of the moving load on the structure. Based on the variable density structure topology optimization method, the equivalent moving load method is proposed to transform the motion of heavy objects on the boom into multiple equivalent working conditions. And according to the structural characteristics and motion form of the boom, the weight coefficient of every equivalent working conditions is assigned. The number of equivalent moving loads is determined in the form of multiple growth, and finally the lightweight cantilever crane boom structure is obtained, which is 32.08% lighter than the original structure, thus verifying the structural topology based on the equivalent moving load method proposed in this paper. The feasibility and effectiveness of the optimization method are also provided for other structural optimization that are subject to moving loads.

1. Introduction

The crane has a complex structure and a large number of parts, which is of great significance for its related lightweight design. At present, the related research work on crane light weighting mainly focuses on the optimization of the structure of the whole machine or parts of the crane by using related design methods such as topology, shape and size optimization. Wang[1] et al. studied the topology optimization of the crane telescopic boom section, and used the topology optimization method to design the boom section. Li[2] et al. used the continuum topology optimization method to design a new type of main beam of the bridge crane, which greatly reduced the weight of the main beam under the condition of ensuring the strength and rigidity of the main beam. However, for structures with special types of loads such as cantilever cranes, traditional structural optimization methods are often difficult to obtain better optimization results. If it can combine the characteristics of its mobile load and consider the influence of different position forces on structural optimization, and establish a structural topology optimization model including structural stiffness and satisfying the manufacturing process, it will greatly help the lightweight research of cantilever crane structure.

2. Moving load and EML method

2.1. Load on the boom

In the process of carrying heavy objects, the cantilever crane moves in a straight line on the track formed by its boom. During this process, the gravity of the weight is applied as a load on the boom of the cantilever crane. The direction and magnitude of the gravity of the object do not change with time, but as the object moves, the position of the load on the boom changes with time. Therefore, during the lifting process, the weight applied to the boom is a kind of moving loads[3,4].

The equivalent moving load(EML) method is designed for special types of loads, such as moving loads. It divides the process of continuous action into many parts. Similar to the data acquisition for the entire motion process, *N* points with static load information at a certain moment are obtained and passed. These points are weighted through the trajectory feature, and finally *N* static loads are respectively established into *N* equivalent working conditions, thereby providing services for subsequent related work, such as force analysis and structural optimization.

2.2. Equivalent moving load method

2.2.1. Physical model. The equivalent moving load method is applied in the optimization of the boom structure of the cantilever crane. Considering the actual movement as a cycle in the whole movement process of the moving load on the boom. At this time, the movement track of the load on the boom is regarded as a straight line is shown in Figure 1(a); the moving load formed by the gravity of the weight carried by the cantilever crane on this straight line can be equivalent to the point in Figure 1(b); the equivalent process is completed by fitting the trajectory line at the load point equivalent to the load method, as shown in Figure 1(c).

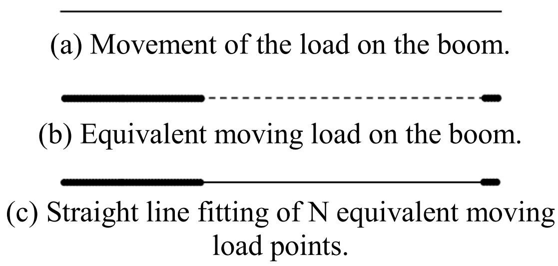


Figure 1. Principle of the EML method.

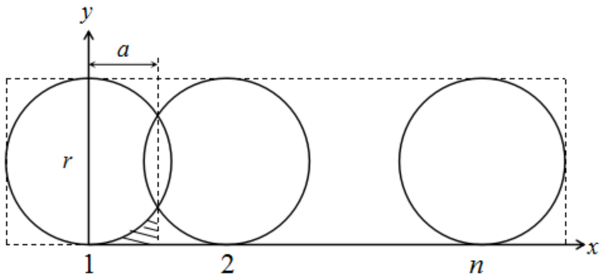


Figure 2. Calculation of equivalent accuracy of equivalent moving load method.

2.2.2. Mathematical model. After the equivalent, the position points of each working condition are sequentially connected to form the total length *L* of the moving load moving track, and the distance between the adjacent two points is:

$$a = \frac{L}{N-1} \tag{1}$$

Let the radius of the circle connected to the total length *L* of the moving load be *r*, as shown in Figure 2, according to the geometric relationship, the curve formula for calculating the shaded portion of the circle which is intercepted by the straight line $x=a$ in the first quadrant is:

$$y = r - \sqrt{r^2 - x^2} \tag{2}$$

Let the area of the shaded part be *s*, and the total area of the inscribed circle and the plane of the boom is *S*, then:

$$\begin{aligned} s &= \int_0^a \left(r - \sqrt{r^2 - x^2}\right) dx \\ &= ar - \frac{a}{2}\sqrt{r^2 - a^2} - \frac{r^2}{2}\arcsin\frac{a}{r} \end{aligned} \tag{3}$$

$$S = 4s(N-1) \tag{4}$$

Bring equation (3) into equation (4),

$$S = 4(N-1)\left(ar - \frac{a}{2}\sqrt{r^2 - a^2} - \frac{r^2}{2}\arcsin\frac{a}{r}\right) \tag{5}$$

When $N \to +\infty$ and $a \to 0$, $S \to 0$, which means the more the number of circles, the closer it is to the shape of the plane of the boom; similarly, in the EML method, the larger the number of equivalent working conditions is, the closer it is to the real moving load after equivalent.

2.2.3. Calculation of weight coefficient of equivalent working condition. Taking the cantilever crane boom as an example, the weight calculation of each working condition is deduced. As shown in Figure 3, the cantilever crane boom is simplified as a cantilever beam, and *N* equivalent working conditions are equally divided on it, and when the total number of the equivalent working conditions is *N*, the weight of the *N*-th equivalent working condition is a_N.

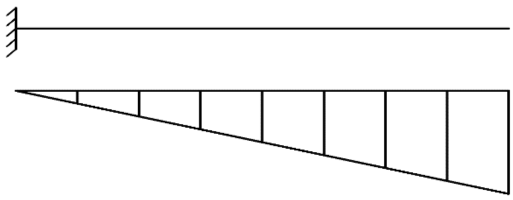


Figure 3. Weight calculation of the EML method.

If the sum of the weight of *N* equivalent working conditions is 1, and the weight of every equivalent working condition is proportional to the its located position, then:

$$\begin{cases} a_1 + a_2 + \cdots + a_N = 1 \\ \dfrac{a_1}{1} = \dfrac{a_2}{2} = \cdots = \dfrac{a_N}{N} \end{cases} \tag{6}$$

where, *N* is the total number of the equivalent working conditions, a_N is the weight of the *N*-th equivalent working condition. By solving equation (6), the weight of the *N*-th equivalent working condition when the total number of operating conditions is *N* can be obtained, that is,

$$a_N = \frac{2}{N+1} \tag{7}$$

3. Mathematical model of topology optimization based on EML method

In order to obtain the optimal performance of the optimization result, a comprehensive analysis of the determination of the deletion or retention of the element under multiple working conditions is required [5,6]. In the variable density method, each working condition is usually used as a single objective optimization function. By using the multi-objective optimization method, all working conditions are weighted to establish a comprehensive objective function. If and only if the relative density of a certain element can be 0 under every working condition, the element is deleted from the structure. The established objective function is as follows:

$$\begin{cases} \min\ F(x) = \sqrt{\sum_{i=1}^{N}\left[a_i C_i(x)\right]^2} \\ \text{s.t.}\ \begin{cases} V \le fV_0 \\ F_i = K_i U_i\ (i = 1, 2, \cdots, N) \\ 0 < x_{\min} < x \le 1 \end{cases} \end{cases} \tag{8}$$

where, *x* is the design variable, which is also the relative density of each element, $x_{\min}$ is the minimum of *x*, to avoid singularity, it is usually set to 0.001. *F(x)* is the integrated objective function, *i* is the serial number of the working condition, $C_i(x)$ is the structural compliance value under the *i*-th working condition, $C_{\min}$ and $C_{\max}$ are the minimum and maximum structural compliance value respectively. *V* is the volume of the optimized structure, and V_0 is the original volume. f is the volume percentage. F_i, K_i, and U_i are the external force matrix, stiffness matrix and displacement matrix of the structure in the i-th condition respectively.

4. Topology optimization design method and process

Flow chart of the topology optimization block diagram based on the EML method is shown in Figure 4. The process of the object moving along the cantilever crane boom is equivalent to the uniform multiple working conditions through the EML method[7]. During the moving process, the size and direction of the load are unchanged, only the position of the load point changes. Therefore, the effect of the moving load on the structure is basically the same, and the optimization objective function can be optimized by the method of equation (8).

5. Structural topology optimization finite element model

Based on the above method, the geometric model of the cantilever crane boom is established by Pro/Engineer 5.0 software, as shown in Figure 5. Based on the established geometric model, the finite element optimization model of the cantilever crane boom is established by using the OptiStruct module in the HyperWorks 11.0 software, as shown in Figure 6. The material used for the boom is S45C, which is meshed into 200337 elements. The fixed constraint is applied to the leftmost position where the cantilever crane column is connected, and the gravity of the weight is applied to the boom as a load. The lower edge rises in different positions. Set the riser around the boom to a non-optimized area with the inner material of the boom set to the optimized area. The number of equivalent operating conditions is set according to the condition of 2 times increase, and can be stopped when the optimization result tends to be stable, which is 1, 2, 4, 8, 16, ... According to the number of working conditions, the weighting coefficients of each working condition can be calculated separately by combining equation (1) and (2).

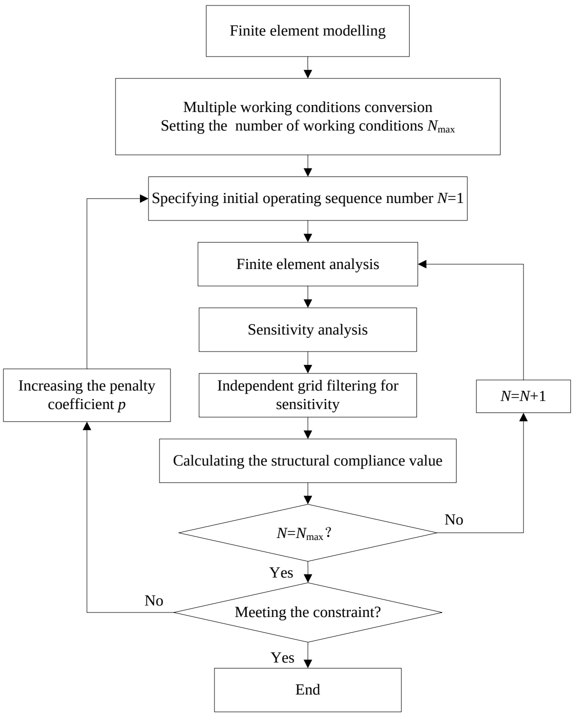


Figure 4. Flow chart of structure topology optimization of cantilever crane boom based on equivalent moving load method.

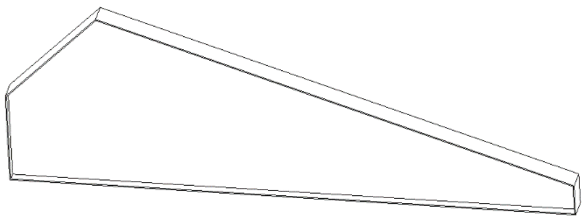


Figure 5. Geometry model of cantilever crane boom.

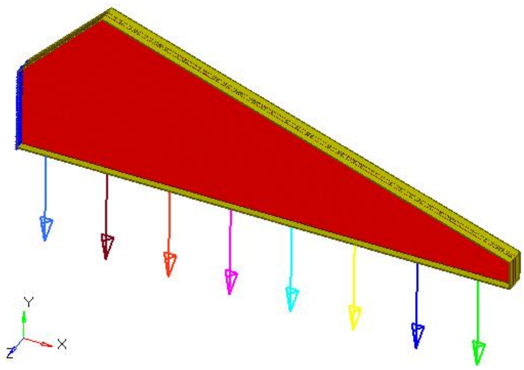
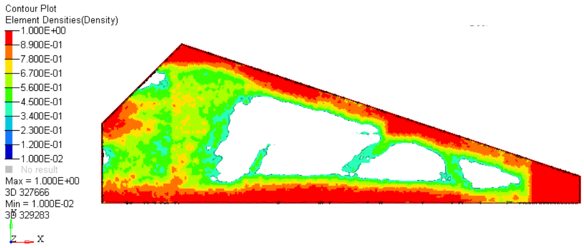


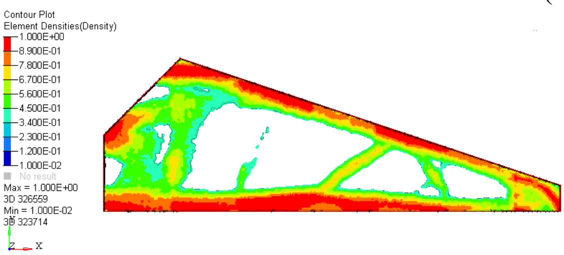
Figure 6. Finite element optimization model of cantilever crane boom.

6. Optimization results

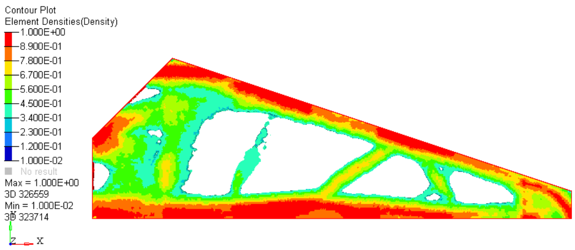
According to the above structure topology optimization model and optimization process, the topology of the boom structure with the different number of equivalent working conditions is optimized. The topology optimization results are shown in Figure 7. Area with color filled in the figure shows the material left, and the white area indicates that the material is removed here.



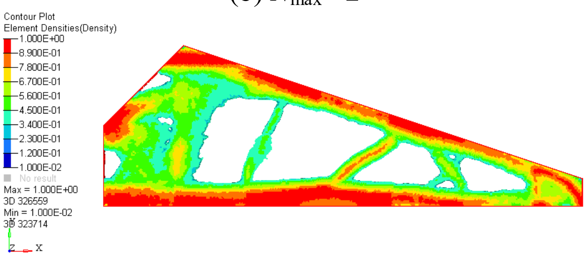
(a) N_{max}=1



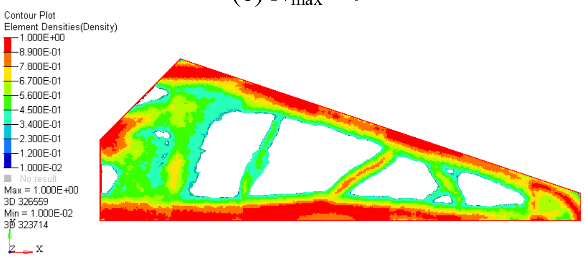
(b) N_{max} =2



(c) N_{max} =4



(d) N_{max} =8



(e) N_{max} =16

Figure 7. Optimization results with the different number of equivalent working conditions.

When the number of the equivalent working conditions is small, especially in Figure 7(a), the color boundary of most of the material areas on the left side is turbid, and the main support structure has not yet formed. Therefore, when the number of the equivalent working conditions is small, the optimization process can obtain feasible solutions, but the numerical instability in the topological result is serious, and the key features have not been fully formed. The number of the equivalent moving load conditions increases by a factor of 2, as shown in Figure 7(b), 7(c), and 7(d). The numerical instability of the large material area in Figure 7(a) has been controlled, and the key support structure in the boom structure is gradually clear.

As the number of the equivalent working conditions increases exponentially, the optimization results gradually become stable. In the optimization result, the contact position between the optimized area and the non-optimized area is all close to red, and the relative density of the element is close to 1, indicating that the material needs to be greatly retained, so that the cantilever crane boom structure has greater rigidity. The boom will not be severely deformed during heavy loads; the material near the contact position of the boom and the column (left side of Figure 7(d), 7(e)) is sufficient, and the root structure of the cantilever beam is subjected to the load process. In the case of large stress concentration, sufficient material is required to release the deformation energy; the rest of the boom is relatively removed from the material, and the structure is mostly in the form of a truss, which ensures the rigidity of the cantilever crane boom is sufficient. Underneath, the weight of the boom is greatly reduced, and the purpose of weight reduction is achieved.

According to the stable topology optimization result, the cantilever crane boom structure is reconstructed, and the lightweight cantilever crane boom shown in Figure 8 is obtained. The optimized cantilever crane boom structure is better than the original structure. The quality is reduced by 32.08%.

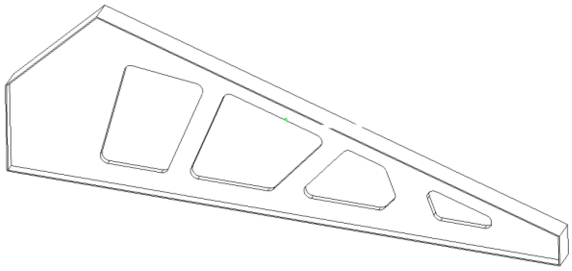


Figure 8. Lightweight cantilever crane boom.

7. Conclusions

In this paper, based on the variable density structure topology optimization method, aiming at the moving load of the cantilever crane boom, a structural topology optimization method based on the EML method is proposed to study the lightweight structure of the cantilever crane boom structure. By transforming the EML of the heavy object lifting process, the number of the equivalent working conditions is set by the multiple growth mode. When the number of the equivalent working conditions is 8, the optimization result is stable; the boom is light according to the topological result. After lightweight, the quality of the structure is reduced by 32.08% compared with the original structure. The optimization process shows that the structural topology optimization method based on the EML method proposed in this paper is effective and feasible, and provides design ideas for other lightweight design of structures subjected to moving loads.

Acknowledgments
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