Research on structural optimization design for shield beam of hydraulic support based on response surface method

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Abstract

The shield beam is the main load-bearing component of the hydraulic support. The structural optimization design of one shield beam is fulfilled by the response surface method. Using the weight as the objective function, the structural optimization mathematical models of shield beam is set up. The experimental design is performed in the ANSYS software and uniform design. The maximum stresses of shield beam are gotten in the different sizes. The response surface models of design parameters and maximum stresses are fitted by the least squares method. The structural optimization design of shield beam is completed by the random direction method. This research implements the structural optimization design of hydraulic support shield beam in a modern design method, and provides a valuable guidance for the hydraulic support research and development.

Keywords: hydraulic support, shield beam, structural optimization design, response surface method.

Introduction

The shield beam is one of the main components of the hydraulic support to bear load. Optimizing the design of the shield beam structure can reduce its weight, which plays an important role for the sustainable development of coal machinery enterprises.

Traditional structural optimization of the shield beam structure can be roughly divided into two types.One is that, according to the theory of material mechanics or mechanical formula, the response of the structure can be computed and the design variables and objective functions can be chosen, then to optimize the design using efficient optimization algorithm (Liu, 2007). For numerous simplifications to models, this method would yield the optimization results more-conservative outcome.While the other is that, the response of the structure is obtained by using finite element software and is chosen as the constraint condition, then to select the suitable optimization strategy for more accurate structure optimization design (Yao, 2011a).This approach, where each iteration will be made during the optimization process with finite element calculations, is running slowly.

To overcome the insufficiency of above traditional optimal design methods, by using the response surface methodology, this research has realized the structure optimization of shield beam for a certain type hydraulic support. With section dimensions of the shield beam as variables, ANSYS is used to calculate the stress of the shield beam under partial loads, and the response surface method of uniform design experiment is applied to obtain the functional relationship between stress values and section dimensions of the shield beam. For the weight reduction purpose, the structure optimization design of shield beam is performed under the constraints of structure strength and geometrical dimension. It is proved that the optimization method is feasible and effective by finite element analysis and validation results.

Optimization Based on Response Surface Method

The optimization based on response surface method generally includes such certain steps as, experiment design, response surface model, and searching for the optimal point (Liang, etc.,2010).

Experiment design is for the sake of scientific and reasonable arrangement of test schemes with fewer experiments to get more properties of design space (Kleijnen, 2005a). A scientific experiment design can arrange various experimental factors reasonably and analyse test data effectively, thus realizing more rich and reliable data obtained with using less resources. Commonly used experimental design methods are full factorials、orthogonal design of experiment and uniform design experimentation, etc.

The uniform design experimentation, which will distribute design points evenly within the design space, is chosen in this research. Compared with other methods, the uniform design experimentation can require less experiment times, and improve the precision of response surface to a certain extent (Li, etc.,2005b). Using this approach, several numerical simulation tests are carried out to obtain a series of design points, whose number and locations are determined. On this basis, the function relationship between control variables and target variables is established with regression method, namely, response surface model. The response surface model reflects the function relationship between target variables (dependent variable) and several control variables (independent variables). As this function relationship is generally curve or curved surface, which is called as response surface model.

Because the response surface model is based on series of regression of test data, the quality of regression analysis directly determines the accuracy of response surface model (Todoroki, A. and Ishikawa, T., 2004). In the field of structural mechanics, the response surface function model often adopts the quadratic polynomial forms, such as

$$Y(X) = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij} x_i x_j \tag{1}$$

where, a_0, ai and aij are undetermined coefficients, x_i (i=1,2,…n) are basic variables. In order to simplify the calculation and avoid application range restrictions for the response surface, the constant term, first-order term and second-order squared are remained, and the second-order cross term is neglected, namely, the simplified form is

$$Y(X) = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^2 \tag{2}$$

Searching for the optimal point in the generated response surface model typically includes to select the design objectives, constraints and the optimal algorithm. For different situations, the mathematical constraints are appended to the model, the design objectives and a series of the search algorithms for the optimal point are provided, such as gradient algorithm, random direction method, penalty function method, etc. The random direction method, which possesses the easy procedures and fast convergent rate, is adopted here.

The Response Surface Model Establishment

Shield Beam Statics Analysis

The shield beam of a certain type hydraulic support is taked as the research object. Finite element model for the shield beam is established under ANSYS environment, then the shield beam is meshed freely with SOLID187 element. According to the technical specifications and load-bearing situation of hydraulic support under partial loads (Qin, etc.,2011b), the corresponding boundary conditions and loads are applied, and ANSYS structural statics analysis is performed to obtain the stress distribution and deformation conditions for the shield beam, as shown in Figs. 1 and 2. The figures show the shield beam's stress situation and deformation under partial loads, where the maximum stress value of the shield beam is 359.61 MPa, and the maximum deformation is 8.96 mm.

To verify the reliability of the finite element analysis, the real physical prototype stress test for the shield beam is also made. According to the characteristics of stress distribution of the shield beam, paste positions of the foil strain gauge are determined for the physical stress tests, and the stress values of the test points are obtained. The locations of the testing points are shown in Fig. 3. At the same time, the corresponding 6 positions at finite element model of shield beam are selected too, where the average stress results are recorded. A comparison of finite element calculation results and measured values is shown in Table 1.

The finite element results and the experimental results are not consistent to a certain degree, which is caused by the test error and calculation error. The long-time experiment results in unstable working environment of the strain gauge, possible different characteristics of each strain gauge, and angular deviation and position deviation for the gauge patch, all these factors will lead to test errors. When finite element model is being simulated, parameter settings, grid division and the differences among the constraint boundary conditions will cause calculation errors. Therefore, it is possible to cause larger relative error of some individual points.

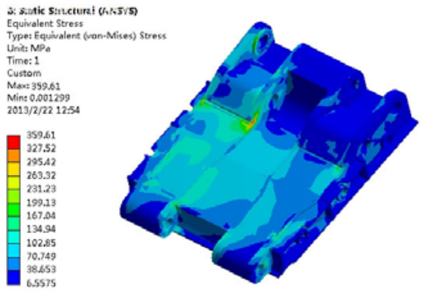

Figure 1. Shield beam's stress distribution

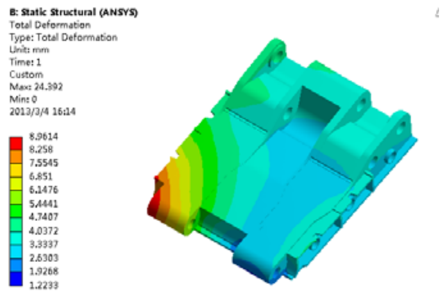

Figure 2. Shield beam's deformation

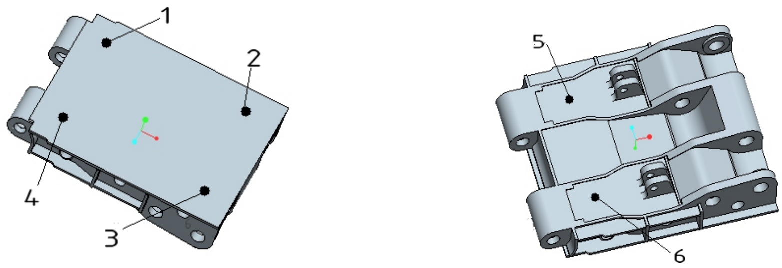

Figure 3. Locations of test points

Table 1. Experimental verification

Number of measuring points	Finite element results/MPa	Measured results/MPa	Relative error/%
1	129.96	120.37	7.97
2	56.36	53.73	4.89
3	42.52	46.96	-9.46
4	164.05	138.04	18.84
5	322.84	305.35	5.72
6	113.24	120.28	-5.85

Uniform Design Experimental Analysis

As shield beam's structure is complex, there are more parameters affecting the component strength. Since the distance between the shield beam's front and back hinged points is already determined during overall design of hydraulic support, the lightest weight will be treated as the optimization objective of shield beam. In other words, the minimum sectional area will be regarded as optimization objective (Zhu, etc., 2012). The shield beam, made up of upper and lower cover plates and vertical ribs, is a box welded structure with a cross section of 5 cavities, which is shown in Fig. 4.

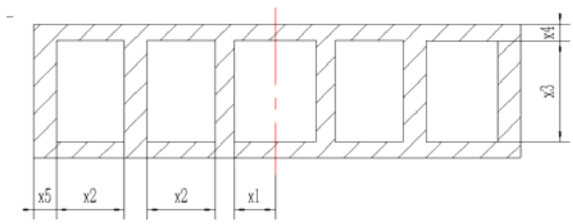

Figure4. The shield beam's cross section

Where, x_1 is the distance between the first cavity and middle plane, x_2 is the width of the second and third cavities, x_3 is the height of the cavity, x_4 and x_5 are the thickness of upper and lower cover plates and the thickness of the vertical rib, separately.

In this paper, the uniform design experimentation is used to carry out response surface experiments. Through the parameterized modeling to realize the change of size of thickness, and the finite element analysis of each group of dimensional data, we can obtain the maximum stress value of the shield beam. The quadratic polynomial without cross terms is taken as the response surface equation which contains 5 parameters and 11 unknown coefficients (that is equal to 2n+1, n is the number of parameter). So, 16 times orthogonal tests, namely including 16 levels 5 parameters, can be determined and performed. The test results are shown in Table 2.

Table 2. Uniform test table

Times	x_1/mm	x_2/mm	x_3/mm	x_4/mm	x_5/mm	σ_{max}/MPa
1	190.00	128.00	160.00	24.33	21.20	340.51
2	193.33	138.00	172.00	27.00	20.13	334.67
3	196.67	148.00	150.00	24.00	19.07	356.14
4	200.00	124.00	162.00	26.67	18.00	364.59
5	203.33	134.00	174.00	23.67	21.47	327.02
6	206.67	144.00	152.00	26.33	20.40	350.47
7	210.00	120.00	164.00	23.33	19.33	346.41
8	213.36	130.00	176.00	26.00	18.27	352.32
9	216.67	140.00	154.00	23.00	21.73	340.67
10	220.00	150.00	166.00	25.67	20.67	346.29
11	223.33	126.00	178.00	22.67	19.60	325.40
12	226.67	136.00	156.00	25.33	18.53	351.94
13	230.00	146.00	168.00	22.33	22.00	350.93
14	233.33	122.00	180.00	25.00	20.93	336.66
15	236.67	132.00	158.00	22.00	19.87	335.18
16	240.00	142.00	170.00	24.67	18.80	347.15

Using the least-square method to fit the response surface function,

$$y_e = 3849.4835 - 2.5428x_1 - 16.7542x_2 - 1.3887x_3 - 12.6922x_4 - 181.4884x_5 + 0.0061x_1^2 + 0.0625x_2^2 + 0.0026x_3^2 + 0.3031x_4^2 + 4.4595x_5^2 \tag{3}$$

where y_e is a response value of the maximum stress.

According to the evaluation formula of multiple correlation coefficient (equation (4)), we can evaluate the fitting degree and get R^2 for every response surface function. The relative high evaluation index (R^2=0.9664) for equation (3) proves that the fitted response surface function is suitable, which means that the response surface experiment is well with respect to practical simulation, and it will provide a good foundation for the next step of structure optimization.

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{4}$$

The Optimization Design

Optimal Design Mathematic Model

The lightest weight of the shield beam, is equivalent to the minimum cover of cross section area of the shield beam. From the Fig.2, the objective function can be made as

$$F(X) = 2x_4(2x_1 + 4x_2 + 6x_5) + 6x_3x_5 \tag{5}$$

The constraint conditions of the structural optimization on shield beam are divided into the following kinds:

Strength conditions: It is ensured that the the maximum stress value of the shield beam under partial loads must not exceed the allowable stress. There is

$$y_e \le \sigma_s / n_s \tag{6}$$

σ_s —the material's yield limit (MPa); n_s —allowable safety factor.

The thickness restrictions of the shield beam: Considering the factors such as the ventilation section, the gas emission, pedestrians and the overall effect of the support, a thickness range of shield beam is often specified in the design. There is

$$T_{\min} \le x_3 + 2x_4 \le T_{\max} \tag{7}$$

$T_{\min}$ —the minimum thickness of the shield beam; $T_{\max}$ —the maximum thickness of the shield beam (mm).

The overall thickness restrictions of the abdomen: Considering that the shield beam of hydraulic support has certain stiffness, the abdomen design should define a minimum thickness. There is

$$-2(x_1 + 2x_2 + 3x_5) \le -c_{\min} \tag{8}$$

$c_{\min}$ —lower bound of the total thickness of the abdomen (mm).

Boundary conditions: The value of the parameter is restricted by various specification of the plate, also by the overall or partial stiffness and deformation. Therefore, the design variables are within a certain range. There is

$$l_i \le x_i \le u_i \quad i = 1, 2, \cdots, 5 \tag{9}$$

l_i —the lower bound of the variable (mm); u_i —the upper bound of the variable (mm).

So the mathematical model can be summarized as follows:

$$\text{Min } F(X) = 2x_4(2x_1 + 4x_2 + 6x_5) + 6x_3x_5$$

$$X=[x_1,x_2,x_3,x_4,x_5]$$

$$\text{s.t.} \begin{cases} y_e \le \sigma_s / n_s \\ T_{\min} \le x_3 + 2x_4 \le T_{\max} \\ -2(x_1 + 2x_2 + 3x_5) \le -c_{\min} \\ l_i \le x_i \le u_i \quad i = 1, 2, \cdots, 5 \end{cases}$$

Optimization and Validation Results

In this paper, the random direction method is programmed with MATLAB to solve optimization model. Combining with actual production requirements, the optimal results of design variables for engineering process can be obtained as shown in Table 3.

Before optimization, the cross sectional area of the shield beam is 0.0769 m^2, and through optimization, the cross sectional area of the shield beam decreases to 0.0678 m^2. That means, the shield beam themselves in weight will be reduced by 11.8%.

According to the above optimization, the shield beam has to be modeled again. Under the unilateral loading conditions of top beam, the finite element analysis for the shield beam is performed again. The contours of stress and displacement of the optimized shield beam are shown in Figs. 5 and 6.

Table3. Design variables optimization results

Parameters	Upper limit value/mm	Lower limit value/mm	Original value/mm	Optimal value/mm
x_1	190	240	225	221
x_2	120	150	140	135
x_3	150	180	170	172
x_4	20	28	25	22
x_5	15	22	20	19

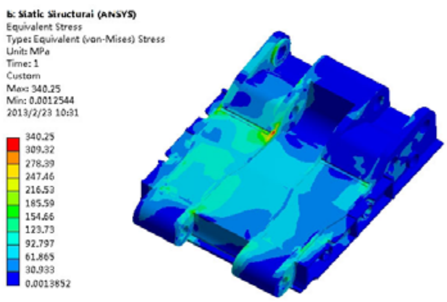

Figure 5. Optimized stress distribution of the shield beam

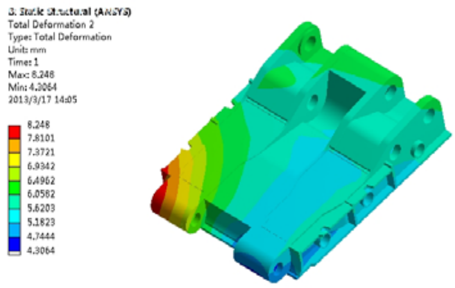

Figure 6. Optimized deformation of the shield beam

Conclusions

(1) Based on the response surface method, the structural optimization on shield beam is proposed. And the response surface method and the finite element analysis are applied for shield beam structure optimization. The shield beam sectional dimension of a certain type Hydraulic Support is optimized to verify the practicality of the method.

(2) The independent variables of response surface function are chosen according to sectional dimensions of shield beam, and the experiment design is carried out by using uniform experimental methods. The least-square is used to fit the response surface function, which can approximately reflect the relation between the sectional dimension and the maximum stress.

(3) Since the response surface function fitting is independent of the specific structure shape, the method has a certain universality and can be applied to other structures optimization for hydraulic support.

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