Design of main frame of tunnel lining trestle with multivariate response model

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Abstract. The main frame of the key equipment trestle in the tunnel lining rapid construction complete set process is the research object. Taking the main frame structure optimization and light mass of the trestle as the research goal, the Central Composite Design test design method is used under the conditions of using the structural strength and stiffness. The primaries of the multi-structure size parameters are subjected to sensitivity analysis, and the sizes that have large influence on the structure mass, the maximum deformation, and the maximum equivalent stress are selected as the final design variables. The response surface model between the design variables and the optimization targets is established, and the global optimal solution of the design variables is solved by the MOGA algorithm. The analysis results show that the optimized structural section parameters meet the requirements of tunnel rapid lining construction, and the mass is reduced by 7.9%.

1. Introduction

With the rapid development of tunnel construction technology in China, advance and one-time full-scale construction of inverted arch is adopted in order to shorten the working time of inverted arch construction, improve the durability of the structure, improve the stress state of the structure and solve the problems of tunnel seepage and leakage. However, in the construction of inverted arch, the construction process of initial support, lining and backfilling of inverted arch will inevitably affect the normal operation of other processes such as tunnel excavation and elementary transportation of slag and soil. At present, the solution to this problem is to erect an invert trestle over the inverted arch. The invert trestle integrates the mechanical construction equipment of inverted arch lining, which is of great significance to ensure the quality of inverted arch lining, improve the efficiency of inverted arch construction, simplify the process and reduce the cost of inverted arch construction[1].

The tunnel inverted arch trestle has been studied a lot by domestic and foreign scholars. Document[2] takes different transportation modes in tunnels as objects. The design and construction of track inverted arch trestle with multi-span piers and single-span steel girder inverted arch trestle are discussed, which ensure the smooth transportation line and the orderly construction of the inverted arch trestle. Document[3] checks the strength and stiffness of 6m long inverted arch trestle made of I-20 I-steel under the maximum dynamic load, which provides a reference for the structural strength checking of simple inverted arch trestle. Document[4] introduces the main structure and system design of self-developed inverted arch crawler trestle and shows the advantages of this equipment over ordinary inverted arch trestle through its application in concrete construction. In Document[5], a 24m fully automatic hydraulic inverted arch trestle with safety, reliability, long span and flexible movement is designed by extensive
investigation and practical research. The above papers mainly study the design of inverted arch trestle, application in concrete construction and structural checking, but seldom optimize the design of trestle structure. However, due to the narrow space in the tunnel, various types of construction projects and complex technology, many restrictions have been put forward on the use of large-scale machinery and equipment. This paper optimizes the main frame structure of 30m tunnel lining inverted arch trestle, improves the mechanical performance of the structure, reduces the use of materials, improves the utilization rate of tunnel space and speeds up tunnel construction. At the same time, it also provides some reference value for the design of tunnel lining trestle.

In this paper, ANSYS Workbench software is used to analyse the sensitivity of the section sizes and shape sizes of the main frame of the trestle, and the sizes that have great influence on the mass of the main frame of the trestle are selected. Experiment data is generated by using the Central Composite Design test method. Response surface approximation model is established. Taking the static strength and stiffness of structures under dangerous conditions as constraints, the optimal solution of response surface model is solved by using MOGA (multi-objective genetic algorithm) in ANSYS Workbench software, and the reasonable value of design variables is obtained.

2. Static analysis of main frame of trestle

2.1. Structure composition of trestle

In order to reduce the manufacturing cost of inverted arch trestle and make full use of material properties, the 30m inverted arch trestle produced by a company is to be optimized. The trestle is mainly composed of main girder, middle pillow beam, approach bridge, loading plate, walking trolley, front support frame and middle support trolley. The main structure is shown in figure 1. The main bearing member is the main girder and the middle pillow beam. The main girder is composed of upper and lower flange plates, main and secondary webs, vertical plates and partitions. The main part of the middle pillow beam is H-section steel of type H350×250. Several stiffened plates are added between the upper and lower flange plates of H-section steel. The steel structure of inverted arch trestle is mainly made of Q235B material. The yield strength and tensile strength of Q235B are 235 MPa and 375 MPa respectively.

![Figure 1. Main structure of trestle.](image)

2.2. Static analysis of main frame of trestle

During the construction of the tunnel, the total mass of the construction truck passing through the trestle under rated load is 35t, and the wheelbase is 4.2m. Construction truck is in dangerous condition when it travels to the middle position of trestle. Using HYPERMESH software, 3D Solid187 tetrahedron element is used to mesh the main frame of trestle. The finite element model is shown in figure 2. The grid file is imported into ANSYS Workbench, and the static analysis results are shown in figure 3.

From the results of figure 3, it can be seen that the maximum equivalent stress of the main frame of trestle is slightly less than the allowable stress of the material, and the maximum deformation is 10.752 mm, which is far less than the design requirements of the static stiffness of the main girder specified in the crane design code[6]. Therefore, the design of the main girder and the intermediate pillow girder is too conservative and should be optimized.
Figure 2. Finite element model of main frame of trestle.

3. Model and analysis of response surface of main frame of trestle

When the implicit function relationship between some influencing factors and response values cannot be obtained easily, the response surface method generates a series of experimental data by using a reasonable experimental design method, and uses multiple quadratic regression equation to fit the functional relationship between factors and response values[7]. The optimal solution of the approximate model is obtained by analysing the regression equation. Response surface model is a regression model, which has the characteristics of simple mathematical formula, fast convergence speed and small amount of calculation[8].

3.1. Pre-selection of optimized parameters

The main girder of the main frame of trestle is mainly composed of upper and lower flange plates, main and secondary webs, vertical plates and partitions and the middle pillow beam is composed of H-section steel and stiffened plates. On the basis of not changing the original structure of main frame of trestle, the parameter selection, parameter meaning and parameter range of main girder and middle pillow beam are shown in table 1.

3.2. Sensitivity analysis

Sensitivity analysis refers to the sensitivity of structural objective performance function to structural design parameters[9]. The experiment is designed by central composite design method. There are twelve input variables with a factor of 4. And a total of number of 281 design points are generated. The mass of the main structure of the trestle, the maximum deformation and the maximum equivalent stress under dangerous conditions are taken as the output parameters. In order to improve the efficiency of optimization, sensitivity analysis of the primary parameters is carried out by using ANSYS Workbench software. And the parameters which have great influence on the objective function are selected to be the final parameters. A structural response Y can be determined by parameters (X1, X2, X3, ..., Xn)[10]. The partial derivative of Y for a parameter is the sensitivity of response Y to that parameter.
\[
S = \frac{dg(x)}{dx} \quad \text{or} \quad S = \frac{\partial g(x)}{\partial x_i}
\]  

(1)

ANSYS Workbench sensitivity analysis uses Spearman correlation coefficient to express the sensitivity of structural response \(Y\) to structural parameter \(X\). Through \(n\) times of simulation test with reasonable test method, \(n\) groups of sample points can be obtained. Spearman correlation coefficient can be expressed as:

\[
\rho = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\left[ \sum_{i=1}^{n} (X_i - \bar{X})^2 \right]^{\frac{1}{2}} \left[ \sum_{i=1}^{n} (Y_i - \bar{Y})^2 \right]^{\frac{1}{2}}}
\]  

(2)

In the formula: \(\bar{X}\) and \(\bar{Y}\) mean the average value of \(X\) and \(Y\) respectively. And \(\rho\) is the Spearman correlation coefficient. If the value of \(\rho\) is 0 means that the structural response is not related to the input variable. And the closer the \(|\rho|\) is to 1, the more monotonous the correlation between the structural response and the input variable is. \(\rho\) is the sensitivity of response to input variables. The sensitivity analysis results are shown in figure 4, figure 5 and figure 6.

Table 1. Significance and Range of Primary Selected Parameters.

| Pre-selected parameters | Meaning of parameters                                      | Range of values(mm\(^{-1}\)) |
|-------------------------|------------------------------------------------------------|-------------------------------|
| D1                      | Thickness of upper and lower flange plates of main girder  | 8–16                          |
| D2                      | Secondary web thickness of main girder                      | 8–14                          |
| D3                      | Width of upper and lower flange plate of main girder        | 495–605                       |
| D4                      | Web height of main girder                                  | 1193–1458                     |
| D5                      | Cantilever length of flange plate of main girder            | 18–22                         |
| D6                      | Thickness of stiffened plate of middle pillow beam          | 10–14                         |
| D7                      | Height of vertical plate of main girder                     | 225–275                       |
| D8                      | Width of vertical plate of main girder                      | 6–10                          |
| D9                      | Thickness of vertical plate of middle pillow beam           | 10–14                         |
| D10                     | Thickness of H-section flange plate                         | 8–18                          |
| D11                     | Thickness of H-section web                                 | 6–13                          |
| D12                     | Thickness of main web of main girder                        | 8–16                          |

In sensitivity histogram, the sensitivity value is positive, indicating that the value of output parameters increases with the increase of input parameters. The sensitivity value is negative, which indicates that the value of output parameter decreases with the increase of input parameter[11]. From the analysis results, it can be seen that the parameters D1, D2, D3, D4, D5, D6, D10, D12 have great influence on the output parameters and can be determined as the final design parameters.

3.3. Establishment of response surface

Eighty-one sets of experimental data are generated by using the central composite design method for eight design variables. Standard Response Surface-Full 2nd Order Polynomials method is used to generate second-order response surface function[12]. The second-order response surface model is commonly used in engineering practice and has high accuracy[13]. The functional equation of the second-order response surface can be expressed as:

\[
y = \beta_0 + \sum_{j=1}^{n} \beta_j x_j + \sum_{j=1}^{n} \beta_j x_j^2 + \sum_{j=1}^{n-1} \sum_{j=1}^{n-1} \beta_{ij} x_i x_j + \varepsilon
\]  

(3)

In the formula: \(n\) is the number of variables. \(\beta_0, \beta_j, \beta_i, \beta_{ij}, \varepsilon\) is the coefficient of constant term, first-order term, quadratic term, cross term and error term respectively which can be solved by least-square method. After obtaining the specific equation, the rationality of the equation can be verified by goodness
of fit test, horizontal regression coefficient test and significance test[14]. The established response surface is shown in figure 7, figure 8 and figure 9.

4. Optimization solution

4.1. Mathematical model

With the optimization purpose of lightening the mass of the main structure of trestle, eight parameters determined by sensitivity analysis are selected as final design variable. The meaning of some parameters is the thickness of the plate. In engineering practice, plate thickness is a series of discrete values. However, the parameters are still regarded as continuous variables when optimizing. Finally, the values of the parameters are rounded. A lightweight mathematical model can be expressed as:

$$\begin{align*}
\min & \ y(D) = m(D) \\
\text{s.t.} & \ \sigma_D < [\sigma], f_D < [f] \\
D & = (D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8, D_9, D_{10}, D_{11}, D_{12})
\end{align*}$$

In the formula: m(D) represents the mass of the main beam and the bolster, $\sigma_D$ represents the maximum equivalent stress of the structure, $[\sigma]$ represents the permissible stress, $f_D$ represents the maximum deformation of the structure, $[f]$ represents the permissible deformation. The above model is used to optimize the response surface of the structure.
4.2. Multi-objective optimization based on genetic target

The optimal solution is calculated by MOGA (Multi-objective genetic algorithm) in ANSYS Workbench after fitting the equation of the response surface. MOGA is an algorithm variant based on NSGA-II (non-dominated sorting genetic algorithm II), which can quickly optimize in a large design space. It has ability to avoid the trap of local optimal solution and find the non-dominated solution by fast sorting, retaining elite groups and maintaining the diversity of the population at the same time[15]. To make full use of the properties of materials, the calculation solution is supposed to make the mass of optimized structure smaller, and the maximum deformation and maximum equivalent stress within permissible value. After optimization, three sets of candidate solutions are obtained. The case of the candidate solution is shown in table 2.

4.3. Result analysis

The three sets of candidate solutions given in table 2 are all reasonable optimization solutions. Referring to the values of the design variables in the three sets of candidate solutions, the input parameters are adjusted. D10 represents the thickness of the upper flange plate and should be selected according to the model series of the H-section steel when adjusted. D1, D2, D6, and D12 represent the thickness dimensions of the plate. When adjusting, the thickness specification of the steel in actual industrial production needs to be considered. When the three sets of candidate points are adjusted, the values of the design variables in the three-dimensional model are changed. After calculation, the results of the second candidate points are found to be optimal, and the results of the finite element are shown in figure 10. The analysis of the optimization results is as follows:
(1) Mass
After optimization, the mass of the main structure of the trestle is reduced from 24,248 kg to 22,317 kg, and the mass is reduced by 1931 kg, a decrease of 7.9%.

(2) Static Characteristics Analysis
After optimization, the maximum deformation of the main girder and the middle pillow beam is 14.74 mm, and the maximum equivalent stress is 168.65 MPa, which are still within the allowable range.

Table 2. three sets of candidate solutions.
| Parameters /mm | Group 1 | Group 2 | Group 3 |
|----------------|---------|---------|---------|
| D1             | 8.24    | 8.04    | 8.42    |
| D2             | 8.42    | 8.36    | 8.10    |
| D3             | 528.75  | 504.30  | 527.07  |
| D4             | 1194.30 | 1201.90 | 1303.20 |
| D5             | 23.69   | 21.61   | 19.18   |
| D6             | 8.11    | 11.97   | 13.66   |
| D10            | 10.23   | 9.15    | 11.01   |
| D12            | 8.16    | 8.16    | 8.36    |
| D13/kg         | 20724   | 20552   | 22288   |
| D14/mm         | 22.01   | 20.45   | 15.80   |
| D15/MPa        | 160.94  | 154.48  | 174.72  |

5. Conclusion
Taking the main frame of the key equipment trestle in the tunnel lining rapid construction complete set process as the research object, maximum deformation and maximum equivalent stress of trestle main frame have been obtained through static analysis. Sensitivity analysis of primary design parameters is carried out. The parameters that have significant influence on the mass, maximum deformation and maximum equivalent stress of the research object are selected as the final design variables. The response surface model of design variables and optimization objectives is established with the optimization and light mass of trestle main frame structure as the research objective. MOGA method has been used to solve the optimal solution of the response surface equation. The sizes of the optimal solution solved by ANSYS Workbench are rounded off. After analysis, the mass of the main girder and the pillow beam is reduced from 24248 kg to 22317 kg, and the mass is reduced by 1931 kg, a decrease of 7.9%. Maximum deformation increases from 10.75 mm to 13.51 mm slightly. But it is still within the allowable range. The maximum equivalent stress decreases from 171.38 MPa to 168.65 MPa, with obvious optimization effect, which can provide certain reference value for the research of related trestle.

![Figure 10. Static analysis of optimized main frame of trestle.](a) (b)

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