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Topology optimization Method Research based on submodel method

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Abstract
With the gradual maturity of topology optimization methods, the use of topology optimization technology for fine design of large building structures can reduce the difficulty of traditional experience design, reduce the welding process, and better ensure the node performance. However, when using topology optimization to optimize the design of large building structures, there will be problems such as too large finite element scale and difficult to accurately describe the boundary conditions. To solve this problem, this paper proposes a topology optimization method based on the submodel method, which can greatly reduce the finite element calculation under the premise of accurately describing the boundary conditions of the design domain, and can complete the topology optimization design of large building structures more efficiently.
Keywords: *Topology optimization; Building structure;Submodel method*

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I. INTRODUCTION

Submodel method is also called cut boundary displacement method or specific boundary displacement method. The cutting boundary is the dividing boundary between the submodel and the global rough model. The calculated displacement value on the cutting boundary of the global model is used as the boundary conditions of the submodel. The submodel technique is based on the Saint-Venant principle. When the actual load is replaced by the equivalent load, the stress and strain change only near the place where the load is applied. This indicates that the stress concentration effect occurs only at the location of the load concentration. Therefore, if the boundary of the submodel is far away from the stress concentration region, more accurate results can be obtained within the submodel.

Based on OptiStruct software and submodel method, QiuZhengcheng, QiuGuangyu et al. [1] analyzed the strength and stiffness of high-speed trains with an speed of 400 km per hour, took the middle part of the car body as the design domain, determined the boundary of the submodel and generated the displacement information of the boundary node, and verified the effectiveness of the submodel by comparing the stress diagram of the original structure and the submodel. Through the submodel, the topology optimization design of the car body was carried out, and the optimized concept car could meet the strength and stiffness requirements of the car body under various working conditions while reducing the weight.

Zeng Ziming, Sun Liping [2] et al. adopted the submodel method to carry out topological optimization on the original design structure of the rear cover of traction beam of an engineering rail car, which did not meet the design requirements. Based on the topological optimization results, the rear cover structure was reconstructed geometrically, and the optimal form was determined from the aspects of manufacturing and lightweight. After static analysis of the optimized structure, it is found that the force of the structure under various working conditions meets the requirements under the premise of mass reduction of 11.13%.

Chen Zhihao et al. [3] combined submodel technology with response surface method to optimize vehicle body reliability.

In order to solve the stress concentration problem of prestressed pier of tensed-type anchoring shaft, Si Zheng et al. [4] adopted submodel method to optimize the size of anchoring shaft so as to reduce the tensile stress around the anchoring shaft.

Li Xinkang et al. [5] proposed the method of replacing full-size vehicle body with end-bottom shelf model for fatigue test. The end bottom shelf model and the finite element model of full-size car body are established, and it is proved that the submodel method is feasible to evaluate the fatigue life of subway car body.

In this paper, a topology optimization method based on the submodel method is proposed, which can greatly reduce the calculation scale on the premise of ensuring the calculation accuracy. It not only reduces the calculation scale, but also provides a reference for the future optimization of building structure.

1.1 Submodel method theory

Based on Saint-Venant principle, submodel method is a method of fine analysis of local key areas of structure on the basis of calculating and analyzing the whole model. Meanwhile, submodel method is also called cutting boundary method or specific boundary displacement method. Boundary cutting means that the boundary of the research area is separated from the overall structure, and the displacement information obtained is taken as the basic boundary conditions of the submodel [6], and then the extracted submodel is analyzed separately. Submodel method can be proved from finite element theory. The essence of finite element solution is to solve linear equations, which can be expressed as:

$$[K][D] = [F] \quad (1)$$

Where$K$ is the global stiffness matrix, $D$is the displacement vector to be solved, and$F$ is the external load.

If the displacement vector$D$ is known as D and the rest is D2, the above equation can be rewritten as:

$$\begin{vmatrix} K_{11}K_{12} \\ K_{21} \quad K_{22} \end{vmatrix} \begin{vmatrix} D_1 \\ D_2 \end{vmatrix} = \begin{matrix} F_1 \\ F_2 \end{matrix} \quad (2)$$

Where, Formula 2 can be expanded to obtain:

$$K_{22} \cdot D_2 = F_2 - K_{21} \cdot D_1 \quad (3)$$

It can be seen that the displacement vector D_1 has been transformed into the load term, and then vector D_2 can be obtained, in which the displacement vector D_1 is the displacement condition of cutting the boundary, which verifies the correctness of the submodel method from the perspective of finite element theory [7].

1.2 Topology optimization model of submodel method based on variable density method

The topology optimization model based on the submodel method under given boundary conditions and load conditions is as follows: Under the continuum volume constraint, the overall compliance is minimized as the optimization objective.

$$Find: \{x_1, x_2, \dots, x_n{}^T\} \in R$$

$$Minimize: C = U^T K U = \sum_i^n u_i{}^T k_i u_i = \sum_i^n (x_i)^p u_i{}^T k_0 u_i$$

$$Subjectto: V = f \cdot V_0 = \textstyle\sum_i^n x_i v_i \leq V^* \quad (4)$$

$$F' = K' U_M$$

$$0 \leq x_{min} \leq x_i \leq x_{max} \leq 1$$

C is the overall structure compliance function;$k_i$is the stiffness matrix after optimization of element i;$u_i$is the optimized displacement vector of elementi;V is the total volume of the optimized structure;v_i is the cell volume;V^* is the target optimization volume;F is the force;K is the total stiffness matrix;U is the total displacement matrix;Compared with the traditional topology optimization mathematical model, the submodel-based topology optimization formula changes from F=KU to $F' = K'U_M$, Where F' is the external load on the submodel, including the original load and the cutting boundary displacement equivalent to load; K' is the stiffness matrix of the submodel; UM is the displacement to be solved on the submodel. For the local topology optimization of large complex structures, the submodel method can describe the boundary conditions more accurately than the traditional empirical value, and greatly reduce the number of finite element calculation of some elements in the iterative process of topology optimization, reducing the scale of calculation.

1.3Optimization process

The process is mainly divided into two steps. The first step is to reduce the dimension of the overall structure. After finite element analysis of the overall structure, the node information in the non-design domain is converted to the boundary node by load equivalent, and then the calculated displacement value of the boundary node is applied to the design domain as the boundary condition. So that the node displacement information between the non-design domain and the design domain can be accurately transmitted. Then is the topology optimization process of the design domain. After cutting the boundary displacement method, the internal node information of the non-design domain can be accurately transferred to the boundary of the design domain through the boundary displacement. The accurate application of boundary conditions has an important impact on the topology optimization results.

Topology optimization in this paper was carried out on the topology optimization platform of ansys workbench, and the curtain wall topology optimization process based on the submodel was completed as follows:

1)The finite element model of curtain wall support structure was established and the mesh was divided, and the mesh of topology optimization submodel was refined;
2)Apply the overall structural load and constrain the boundary conditions;
3)For the calculation and analysis of the overall model, the cutting boundary of the design domain and the non-design domain is defined. The displacement results of the cutting boundary after the overall calculation are extracted and applied to the design domain as the displacement boundary conditions；
4)The submodel is analyzed, and the boundary stress value in the whole structure is compared to determine whether the selected boundary is satisfied. If yes, topology optimization within the design domain is carried out; if no, the cutting boundary is selected again.
5)Topology optimization aiming at minimum compliance was carried out for the design domain structure；

1.4Optimization example

The example is a cantilever beam structure, which is divided into two parts: the design domain and the non-design domain. As shown in Figure 1, the structural dimensions are respectively 8m for L_1, 2m for W_1, 2m for L_2, and 0.5m for W_2. The left end of the structure is a fixed support, and the structure is subjected to uniform load F externally, with a size of 20KN.

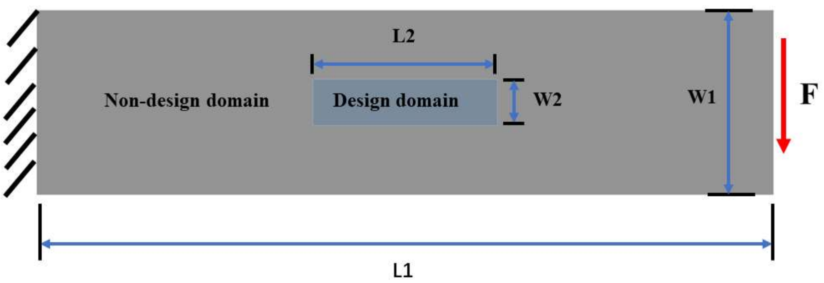


Figure1: Structure partition diagram

The specific steps are as follows: firstly, finite element analysis is carried out on the whole structure to obtain the node displacement value of the cut boundary in the non-design domain, then the information of the boundary node is converted to the boundary node in the design domain, and then verify whether the selected cut boundary meets the conditions. If the conditions are met, topology optimization is carried out on the design domain. The non-design domain area and the design domain area are shown in Figure 2and3.

Figure2:Non-design domain model

Figure3:Non-design domain model

1.4.1 Verification of submodel cut boundaries

It can be seen from the stress diagram of the original structure calculation and sub-model calculation that the maximum stress changes from 4.4681MPa to 4.4679MPa and the minimum stress changes from 2.5943MPa to 2.5937MPa, indicating that the selected cutting boundary meets the requirements and can be calculated in the next step.

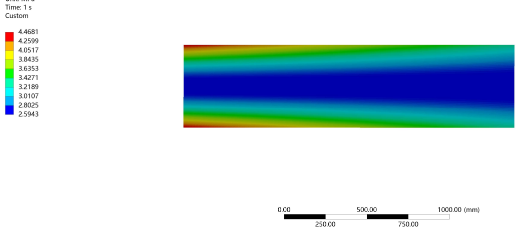


Figure4:Response diagram of submodel in original structure

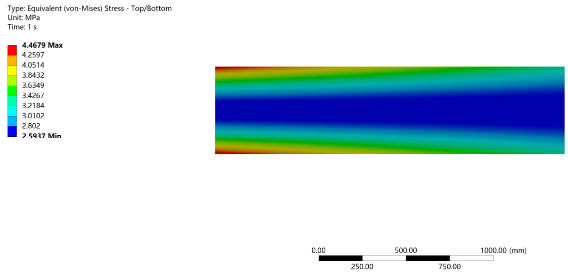


Figure5:Submodel response diagram

1.4.2 Submodel topology optimization

Topology optimization was carried out for the sub-model, and the grid in the structural design domain was set to 5mm and the grid in the non-design domain was set to 20mm. Under the condition of minimum compliance as the objective function and 35% of the reserved volume as the constraint, the minimum member size was set to 15mm and the maximum member size to 30mm, the penalty coefficient was 3, and the structure in the plane was symmetrical. Topology optimization was carried out in the original structure and submodel respectively. The device used for simulation was i7-10750H and the running memory was 16g.

II. RESULT AND DISCUSSION

Topology optimization method based on submodel and traditional topology optimization method are respectively adopted to carry out topology optimization of structures in the design domain. The topology optimization results of the two methods are shown in Figure 6 and Figure 7. It can be seen that the topology optimization results of the two methods are basically consistent, but the difference is that the submodel has less complex force transmission path in the optimization iteration process compared with the original structure. It takes 11min35s for the submodel to complete the optimization, and 1h23min52s for the original structure to complete the optimization. It can be seen that the submodel greatly improves the calculation efficiency on the premise of ensuring the calculation accuracy. Therefore, it is feasible to use submodel to deal with large building structures.

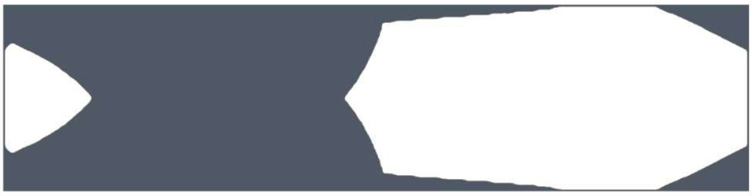
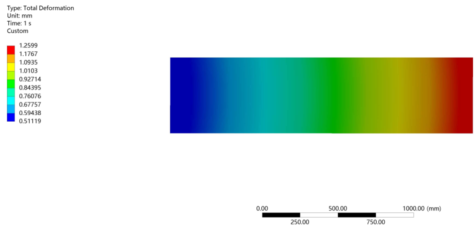


Figure6:Optimization results of conventional methods

Figure7:Optimization results of submodel method

Topological optimization of the cantilever beam design domain was carried out by the proposed submodel topology optimization method, and the optimized structure was obtained. The following figure shows the deformation map and stress diagram of the submodels before and after optimization. By comparison, it can be found that the maximum deformation of the structure does not change after optimization, and the maximum stress of the structure decreases from 4.4679MPa to 4.4578MPa. The maximum stress decreases while the material is greatly reduced. In the topological optimization process, a large number of low-stress elements are removed, which makes the overall stress distribution of the structure more uniform.



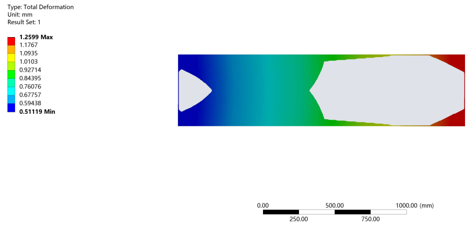
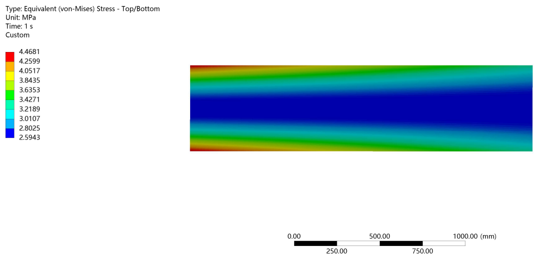


Figure8:Original structure deformationFigure9:Structural deformation after optimization



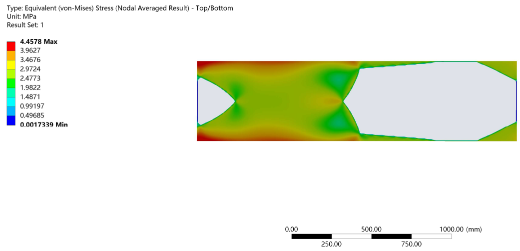


Figure10:Original structure diagramFigure11:Optimized structure diagram

III. CONCLUSION

In this paper, a topology optimization method based on the submodel method is proposed, which can reduce the calculation scale by reducing the invalid paths in the optimization process. The feasibility of the proposed method is verified by an example of a cantilever beam. The results show that the optimization results of the topology optimization method based on the submodel are consistent with those of the traditional topology optimization. However, the operation time of the submodel method is greatly reduced, so the method proposed in this paper is feasible. It can be applied to the topology optimization design of large building structures, and the calculation efficiency can be improved on a large scale without losing the calculation accuracy, which is of great significance for the optimal design of building structures.

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