Topological Optimization Method for Aeronautical Thin-Walled Component Fixture Locating Layout

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Abstract: Fixture locating layout has a direct and influential impact on aeronautical thin-walled component (ATWC) manufacturing quality. The purpose is to develop a topological optimization method for ATWC fixture locating layout to minimize the manufacturing deformation. Firstly, a topological optimization model that takes the stiffness of ATWC as the objective function and the volume of the locating structure as the constraint is established. Secondly, ATWC and the locating structure are regarded as an integrated entity, and the variable-density method based topological optimization approach is adopted for the optimization of the locating structure using ABAQUS topology optimization module (ATOM). Thirdly, through a subsequent model reconstruction referring to the obtained topological structure, the optimal fixture locating layout is achieved. Finally, a case study is conducted to verify the proposed method and the comparison results with firefly algorithm (FA) coupled with finite element analysis (FEA) indicate that the number and positions of the locators for ATWC can be optimized simultaneously and successfully by the proposed topological optimization model.

Key words: aeronautical thin-walled component; fixture locating layout; topological optimization; variable-density method

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0 Introduction

By virtue of high strength and light weight, aeronautical thin-walled component (ATWC) is widely used in the aerospace industry as important parts of fuselage, wings, horizontal stabilizer and vertical stabilizer[1]. Different from rigid component, ATWC always tends to distort and deform during the locating process, thus leading to assembly variation. This problem may adversely affect the final product functionality and the process performance. In order to prevent excessive deformation and supply more reinforcements for buckling prevention at the assembly stage, ATWC is always located in an over-constraint condition, which is the so-called "N-2-1" ($N>3$) locating principle, by a fixture. Hence, the optimization of fixture locating layout is a critical problem for minimizing the assembly deformation of ATWC. Apparently, the key and essential task in fixture layout design is to find the optimal number and positions of the "N" locators on the primary datum plane based on the "N-2-1" locating principle[2].

To solve the aforementioned problem, many scholars and technicians have carried out a lot of research on fixture locating layout design and optimization. In the beginning, finite element analysis (FEA) was employed to predict deformation behavior during locating operations[3]. Cai et al.[4] used FEA and a nonlinear programming method to find the positions of the "N" locating points such that the sum of squares of the nodal deflections normal to the sheet metal surface is minimized. Vallapuzha et al.[5] presented a genet-

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ic algorithm (GA) based optimization method that used spatial coordinates to represent the positions of fixture locating points. Tan et al.[6] employed the methods of force closure, optimization and finite element modeling to find the optimal fixturing configurations. Focusing on the impact of fixture position on the dimensional quality of sheet metal parts after assembly, Camelio et al.[7] presented a fixture design methodology for sheet metal assembly processes, and developed a optimization algorithm combined FEA and nonlinear programming methods to determine the optimal fixture layout. Siebenaler and Melkote[8] used FEA to model a fixture-workpiece system and to explore the influence of compliance of the fixture body on workpiece deformation. In addition, the effects of certain finite element model parameters on the prediction accuracy were also examined by them. Kaya[9] applied GA to optimize fixture layout through integrating a finite element code running in batch mode to compute the objective function values for each generation. According to the sheet metal assembly with resistance spot welding, Li et al.[10] also developed a mathematical representation of deterministic locating by a virtual beam model and a quality design model of fixture planning. A prescribed factor was used to weight the two models. Meshreki et al.[11-12] developed computationally efficient models to predict the dynamic response of the thin-walled components under different fixture layouts for fixture design. Cheng et al.[13] proposed a hierarchical fixture layout model to optimize the base points and locating points of aeronautical thin-walled structure by GA and ants algorithm. Based on the "4-2-1" locating scheme, Lu et al.[14] optimized three fixture locating points on the primary datum surface with GA based on the rigid model considering the robustness and the geometry stability first. Then a back propagation neural network model was built to predict the deformation of the sheet metal workpiece under different fixture layouts. Finally, GA was used to find the optimal position of the fourth fixture locator.

To sum up, there are mainly two approaches for the fixture layout design and optimization of ATWC. One is that, according to the design experience, several possible locators' layout schemes are estimated first. Then, by calculating and comparing the deformation of the component under each locating scheme, a relative optimal layout is chosen. The other way is to combine the finite element method (FEM) with intelligent optimization algorithms (IOAs), and by adjusting the position of the locators in the finite element model in the guidance of IOA to search the final locating scheme. It can be seen, both are the discrete optimization approaches and all the methods just optimize the positions of the locators either with a known number or after the number optimized. Thus, only a relatively good but not the optimum layout can be obtained. Structural topological optimization, as a new branch in structural optimization theory, was developed in the last two decades. Recently, more and more attention has been paid to continuum topological optimization, while the variable-density method is one of its mainstream research techniques. As a consequence, it is of the essence both in theory and application to carry out an exploratory study on fixture layout optimization of ATWC based on continuum topological optimization theory[15-16].

Here, a topological optimization method of fixture layout, to determine the number and positions of the locators on the primary datum surface during the assembly of ATWC based on the "*N*-2-1" locating principle, is proposed. It has the advantage of simple operation and can optimize the number and positions simultaneously. The problem description of the ATWC fixture locating layout is constructed. The basic mathematical model of structural topological optimization is introduced. The flowchart of the proposed method is depicted for the optimization of ATWC fixture layout. And then a case study is conducted to verify the proposed method by comparison with FA coupled with FEA. Finally, the conclusions are drawn.

1 Problem Description

1.1 "N-2-1" locating principle for ATWC

At assembly stage of ATWC during the manufacturing process, fixture is usually used for locating the component accurately and constraining excessive deformation to reduce the dimensional and form errors. The "N-2-1" locating principle is widely recognized in the fixture design for ATWC, which considers that there are "N" ($N>3$) locating points on the primary datum plane, and "2" and "1" on the second and third datum plane respectively. Fig. 1 shows a typical "N-2-1" principle of ATWC, where 4 locators are required in order to support the component on the primary datum plane to avoid excessive deflection. The number "N", which is always more than three, is determined by the dimensional specifications of ATWC. However, since the manufacturing cost, setup time and coupling errors of the fixture increase with the number of fixture locators, a main purpose to optimizing the fixture locating layout based on the "N-2-1" principle is to meet the engineering requirements of ATWC with the least fixture locators at their best positions, that is the optimal fixture locating layout.

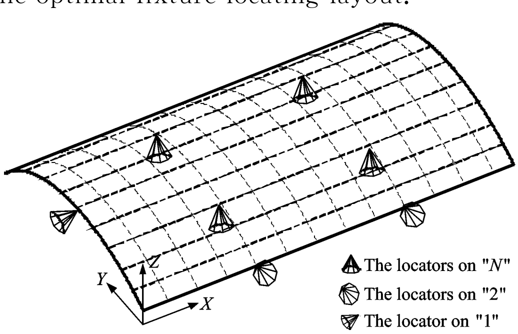

Fig. 1 "N-2-1" locating principle for ATWC

1.2 Fixture locating layout design and optimization

So as to better illustrate the topological optimization method and its application in fixture locating layout design, an integrated system combined ATWC and locating structure, termed as A-L system, is introduced. Considering that the material volume of A-L system after optimization is not more than the original volume, a filling material is assumed at the position of locating structure as the initial state of the optimization, as shown in Fig. 2.

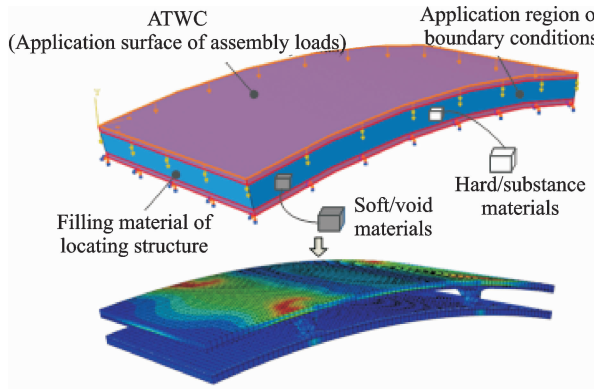

Fig. 2 Finite element model of A-L system

Given an initial material distribution (up), topological optimization produces a new "landscape" (down) by scaling the relative material densities of the elements in the design domain. Elements with large relative material densities are retained while those elements whose relative material densities had become sufficiently small are assumed to be voids. The finite element model of A-L system is illustrated in Fig. 2. At the same time, the assembly loads and constraint conditions are applied on each corresponding region. Here, the structural compliance of ATWC is taken as the evaluation function for the assembly deformation. Thus, with a subsequent model reconstruction referring to the obtained topological structure, a new optimal fixture locating layout is obtained.

2 Mathematical Model of Structural Topological Optimization

As an important part of engineering design, structural topological optimization is to select design variables, establish an objective function, and finally find the optimal value. In topological optimization formulations based on the material distribution concept, discrete variables are usually used for indicating the presence/absence of the material. In this paper, variable-density method is adopted, and the optimization process is to determine the presence or absence of the material for each discrete variable, as shown in Fig. 3. The target of topological optimization is to get an optimum material distribution of a structure. Similarly, the ATWC fixture locating layout design is to find the optimum fixture layout under the constraints of deformation control. Therefore, on the basis of analyzing the basic theory of the topological optimization, this paper presents a novel approach to ATWC fixture locating layout design based on topological optimization method.

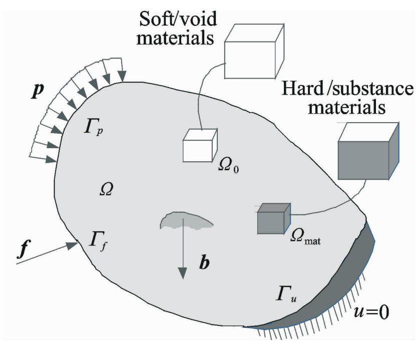

Fig. 3 Continuum structural topological optimization model

Let the design domain occupied by a structure denoted by Ω, with a Lipschitz boundary Γ, and let a body force $\boldsymbol{b}$ be applied in Ω. Ω_0 is the domain where has void materials, while Ω_{mat} has substance materials. Moreover, let a concentrated force $\boldsymbol{f}$ and a uniform traction $\boldsymbol{p}$ be applied along a part of the boundaries Γ_f and Γ_p, respectively, which are the complement of the part of the boundary Γ_u on which displacement components are specified (Fig. 3).

In this section, the topological optimization problem for minimizing the structural compliance is formulated based on nodal density design variables. For a linear continuum structure discretized with finite elements, the global stiffness matrix $\boldsymbol{K}$ is expressed as

$$\boldsymbol{K}=\sum_{e=1}^{N}\boldsymbol{K}_e \tag{1}$$

where N is the total number of the finite elements used to discretize the design domain, and $\boldsymbol{K}_e$ the global-level stiffness matrix of the eth element. In terms of continuous nodal design variables defined above, a relaxed formulation of the minimum compliance problem can be expressed as

$$\begin{cases}\dfrac{\text{Minimize}}{\boldsymbol{\rho}=(\rho_1,\rho_2,\cdots,\rho_N)^{\mathrm{T}}}:C(\boldsymbol{\rho})= \\ \quad \boldsymbol{U}^{\mathrm{T}}\boldsymbol{K}\boldsymbol{U}=\sum_{e=1}^{N}(\rho_e)^p\boldsymbol{u}_e^{\mathrm{T}}\boldsymbol{k}_0\boldsymbol{u}_e \\ \text{Subject to}:\begin{cases}V(\boldsymbol{\rho})-f_vV_0\leqslant 0\\ 0\leqslant\rho_{\min}\leqslant\rho_j\leqslant 1\\ \quad j=1,2,\cdots,N\\ \boldsymbol{F}=\boldsymbol{K}\boldsymbol{U}\end{cases}\end{cases} \tag{2}$$

where $\boldsymbol{F}$ is the external force vector, $\boldsymbol{U}$ the global displacement vector, $\boldsymbol{u}_e$ the element displacement vector, and $\boldsymbol{\rho}=(\rho_1,\rho_2,\cdots,\rho_N)^{\mathrm{T}}$ the vector of design variables. The lower bound of the design variables is set to be $\rho_{\min}=0.001$ for avoiding numerical singularities when solving the equilibrium equations[17]. p is the penalization power (typically $p=3$). In the material volume constraint, $V_0=\int_{\Omega}1\cdot\mathrm{d}\Omega$ denotes the volume of the design domain, f_v is the specified volume fraction ratio and the material volume $V(\boldsymbol{\rho})$ is given by

$$V(\boldsymbol{\rho})=\int_{\Omega}\boldsymbol{\rho}\,\mathrm{d}\Omega=\sum_{j=1}^{N}V_j\rho_j \tag{3}$$

The renewal scheme of the minimum compliance problem is obtained by iteration using a recursion formula as Eq. (4) for density ρ_e

$$\rho_e^{k+1}=\begin{cases}\max\{(1-m)\rho_e^k,\rho_{\min}\} \\ \quad \rho_e^k(B_e^k)^{\zeta}\leqslant\max\{(1-m)\rho_e^k,\rho_{\min}\} \\ \rho_e^k(B_e^k)^{\zeta} \\ \quad \max\{(1-m)\rho_e^k,\rho_{\min}\}\leqslant\rho_e^k(B_e^k)^{\zeta}\leqslant \\ \quad \min\{(1+m)\rho_e^k,\rho_{\max}\} \\ \min\{(1+m)\rho_e^k,\rho_{\max}\} \\ \quad \rho_e^k(B_e^k)^{\zeta}\geqslant\min\{(1+m)\rho_e^k,\rho_{\max}\}\end{cases} \tag{4}$$

where $e=1,\cdots,N$. Here, m is a positive move limit[18], ζ a weighting factor, usually taken to be 1/2[18-19]. B_e is found from the optimality condition as

$$B_e=\frac{-\dfrac{\partial c}{\partial\rho_e}}{\lambda\dfrac{\partial V}{\partial\rho_e}} \tag{5}$$

where λ is a Lagrangian multiplier that can be found by a bi-sectioning algorithm.

Simultaneously, the topological optimization for fixture layout design is a phrase used to characterize design optimization formulations that allow for the prediction of the layout of ATWC locators. That is, the topology or "landscape" of the locating structure is an outcome of the structural topological optimization.

3 Optimization Method

The general flowchart of the topological optimization method for ATWC fixture locating layout based on ATOM is depicted in Fig. 4. Here, E is Young's modulus, ρ the mass density, and ν the Poisson ratio. Moreover, Γ is the Lipschitz boundary of the design domain, $\boldsymbol{b}$ a body force, $\boldsymbol{f}$ a concentrated force, and $\boldsymbol{p}$ a uniform traction.

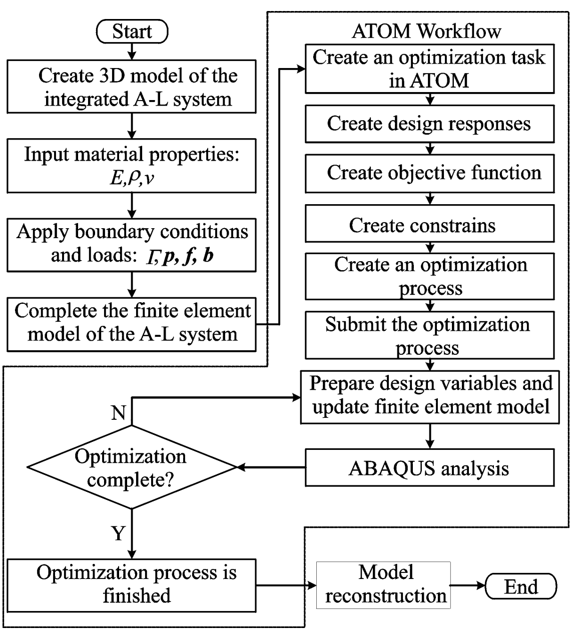

Fig. 4 General flowchart of topological optimization based on ATOM

In the optimization process, the ATOM module in the commercial FEM software ABAQUS is used. Based on the mathematical model of structural topological optimization, the integrated A-L system at different volume fraction ratio f_v is calculated by ATOM to search the optimal locating layout, as depicted in Fig. 5.

Since the optimization process only considers the stiffness of the structure, the obtained optimal topological structure form is ideal and irregular, as shown in Fig. 6. However, in a practical structure design, many other design constraints should be considered, such as the manufacturing process, the standards and specifications of the locating elements, assembly relationship, and so on. Therefore, a subsequent model reconstruction referring to the obtained topological structure is required, as shown in Fig. 7.

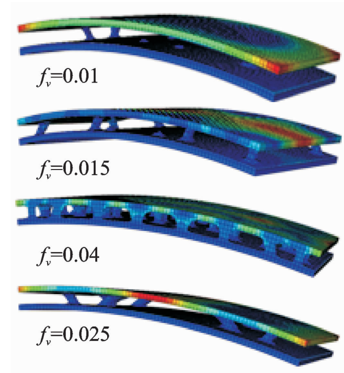

Fig. 5 "Landscapes" with different volume fraction ratios

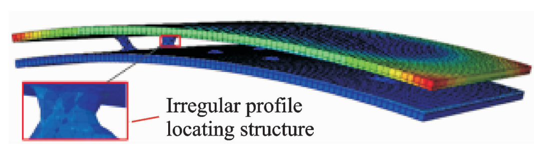

Fig. 6 Original optimal topological structure by ATOM

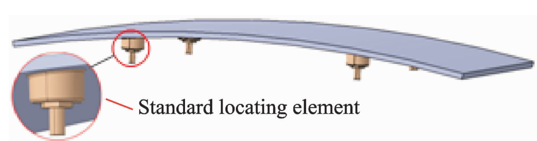

Fig. 7 Final fixture locating layout of ATWC after reconstruction

4 Case Study

To further explain the feasibility and validity of the practical application of the proposed method, a fuselage skin experimental component of a certain aircraft is chosen as a case. The basic dimension and force condition of the component are demonstrated in Fig. 8. The skin material is 7050-T651 aluminum alloy, and the filling material of the locating structure for optimizing is steel. The physical properties of material are listed in Table 1. This paper is to find an optimal fixture layout of the skin component with its maximum deformation value not more than 0. 5 mm (the need of general engineering).

Table 1 Material physical properties used in finite element model

Material property	Mass density/ (10^3 kg · m^{-3})	Young's modulus/ 10^4 MPa	Poisson ratio
Locating structure	7.85	21	0.3
Skin component	2.8	7.12	0.33

Due to the properties of thin wall, large size and low rigidity, the deformation of ATWC during the assembly process is mainly caused by its dead-weight. In this paper, the case study does not consider other external assembly loads, and we only concern with the maximum deformation of the component under the action of its dead-weight.

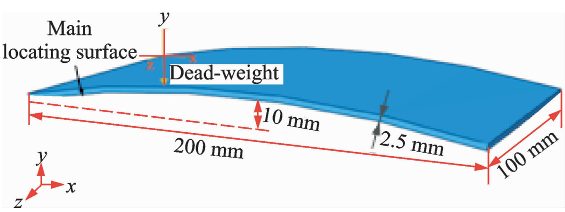

Fig. 8 Thin-walled fuselage experimental component at its locating posture

The finite element model of A-L system is built with the element type is C3D8R (An 8-node linear brick, reduced integration, hourglass control), that is, the 8-node hexahedral linear reduced integral unit. Since the linear reduced integral unit has only one integral node in the center of the cell, the Hourglass Control is introduced to make the finite element calculation more accurate. The total number of finite elements is 19 440, and the boundary condition is a fixed constraint to the bottom surface of the locating structure. With the help of the ATOM module in ABAQUS, the topological optimization of the locating structure is carried out. The optimized fixture locating layout and the corresponding deformation of ATWC are depicted in Fig. 9. According to the obtained topological result, a model reconstruction of the locating structure is conducted. The deformation result of the reconstructed model is illustrated in Fig. 10. It can be seen, the maximum deformation of the fuselage skin component is 0.423 6 mm, which is less than the need of general engineering of 0.5 mm.

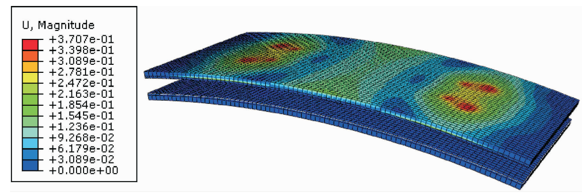

Fig. 9 Original topological optimization result

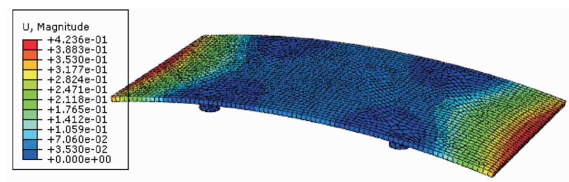

Fig. 10 Final fixture locating layout after reconstruction

For further comparative analysis, the authors of this paper also optimize the same component fixture locating layout based on the "*N*-2-1" locating principle by coupling firefly algorithm (FA) with FEM analysis. The FA is applied to search the optimum layout of the "*N*" fixture locators for the minimum deformation through constant calls to the FEM solver. As a consequence, the final optimization result is shown in Fig. 11. The optimization results by structural topological optimization method and FA are listed in Table 2.

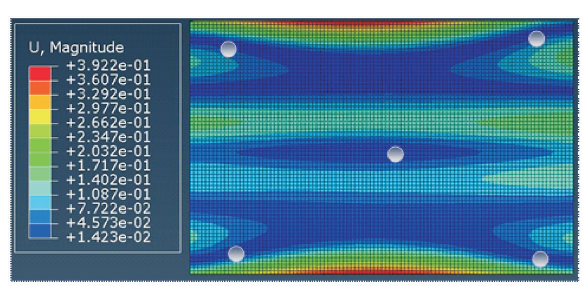

Fig. 11 Fixture locating layout optimized by FA

Table 2 Comparison of results

Result	Number of locators	The maximum deformation /mm
FA optimization result	5	0.392 2
Topological optimization result after reconstruction	4	0.423 6

Compared to the optimization result by intelligent optimization algorithm (FA), the final fixture locating layout by the topological optimization method proposed in this paper has fewer locators to meet the need of general engineering of 0.5 mm. It can reduce the manufacturing cost, setup time and coupling errors of the fixture caused by an increase in the number of fixture locators. Thus, the feasibility and validity of the topological optimization method for aeronautical thin-walled component fixture locating layout proposed in this paper are proved.

5 Conclusions

The structural topological optimization approach based on the variable-density method is proposed to optimize the fixture locating layout for ATWC to minimize its assembly deformation. The major contributions of this paper include:

(1) The topological optimization method for ATWC fixture locating layout design is studied and verified through an aluminum alloy fuselage skin case. The results of case study indicate that the variable-density method based structural topological optimization is capable of obtaining the optimal fixture locating layout for ATWC and the optimization results meet the need of general engineering.

(2) The topological optimization method is compared with FA coupled with FEA in the ATWC fixture locating design. The comparison results show that using the topological optimization model for ATWC fixture locating layout, the number and positions of the locators can be optimized simultaneously.

(3) In view of the design and manufacturing of aeronautical process equipment, the application of topological optimization method can revolutionize the traditional design idea, and provide designers with a feasible and appropriate fixture layout scheme.

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