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TOPOLOGICAL DESIGNING AND ANALYSIS OF THE COMPOSITE WING RIB

The composite structures in the aerospace industry for in recent decades are widely applied however, at the beginning of the 21st century composites are growing rapidly. The largest companies in the aerospace industry are increasing the volume of composites application of in the structures, and nowadays the volume of composites reaches 50%. The different elements of aircraft and even highly loaded structures such as spars, ribs, skin, etc., are currently made from composites. First of all, this is due to the possibility of a significant reduction in the weight of the structure, as well as a decreasing in production costs. The advanced technologies in the engineering software allows to solute different complex problems. One of the main direct of research in the composites is optimization of composite structure due to improving the relative strength and relative stiffness of the composite structure, and improving the efficiency of manufacturing processes. There are a lot of methods of optimizations but currently the topological optimization is the most conceptual and forward-looking method. The main goal of the article is to analyze and estimate the approach for designing wing rib with symmetric laminated plates with the different fiber orientation based on the topology optimization. The following tasks were solved for this: firstly, a topological optimization model was determined. This model was based on maximum stiffness with a specified volume constraint is established. The next step was optimization by the solid isotropic material with penalization (SIMP) model and sensitivity filtering technique; as a result of optimization the topological structures of wing rib with different fibre orientations were obtained. The topological structure and stiffness of the wing rib depend on the fibre orientation. Finally, the corresponding morphing analysis of wing rib with laminated plates is implemented by adopting ANSYS, which verified the anti-deforming capability of topology structure and illustrated the feasibility for designing the wing rib. The result shows that the maximum deformation of optimized structure is 1.57mm, whereas the maximum deformation of the un-optimized structure is 2.02 mm. Under the condition of the same material removals, the optimized structure can decrease by more than 20% deformations.

Keywords: *topology optimization; composite laminated plates; fiber orientation; wing rib.*

1. Introduction

Structural lightweight design plays a vital role in modern aircraft and aerospace industry. One of the most popular methods to obtain a structural lightweight design is adopting innovative structural forms. Generally, structural optimization problems include shape, sizing and topology optimization. The size and shape optimization are two traditional techniques and have been widely employed in the design of bars, beams, trusses, plates, shells and so on [1, 2]. Topology optimization is mostly employed in the phase of conceptual design of structural. In the past decades, structural topology optimization has been developed remarkably in both theoretical studies and practical applications [3, 4], and dedicated review work can be found in [5, 6]. Under the given boundary conditions and design constraints, topology optimization can able to find out an optimal structure using the least material by searching for the most effective load carrying path and material distribution. Compared with size or shape optimization, topology optimization method has a more potentially but full of challenging at the same time.

So far, there are several successful examples of the topology optimization in the design of aircraft structures. In the A380 project of Airbus Industries, the topology optimization has been used as an efficient way to obtain newer and lighter component designs. Such as the design of A380 Droop Nose Ribs, over 1000 kg per aircraft has been reduced in total for the final designs [7]. In the design of the wing leading-edge structure of the Boeing 787, the topology optimization method was first used for the preliminary design. Then, the fine-tuning design is carried out through size and shape optimization. Finally, compared with the Boeing 777, the leading-edge structure’s weight was reduced by 25~45% [8]. Zhu, J et al. [9] used topology optimization methods for design of aircraft wing box ribs. Liu, J. et al. [10] developed a subset simulation-based topology optimization method for additive manufacturing structures.

However, all the topology optimization designs of aircraft structures as mentioned above are aimed at metal materials. With the current rapid increase in the percentage of composite parts used in aerospace structures, it is worthwhile to expand the topology optimization capabilities to include composites. However, the study on topology optimization of composite laminated plates is still in the development stage, and only a few publications have been reported. For examples, Tong et al. [11, 12] developed a topology optimization method for compliant mechanisms with composite laminated plates. Boddeti [13] given an initial attempt at combining fiber angles and topology design of laminated plates under in-plane loadings. Gao et al. [14] proposed a bi-value coding parameterization method to design the fiber orientations and material layout simultaneously.

Stiffness is an important performance index for many engineering structures. In this paper, a topology optimization design method for the aircraft wing rib with composite laminated plates is proposed for maximizing the stiffness of structure. The topology optimization model of wing rib with composite laminates are built using SIMP method [15]. The wing rib with different fiber orientations is generated by method of moving asymptotes (MMA) [16] algorithm and sensitivity filtering technique. Meanwhile, the anti-deforming capability of wing rib and influences of fiber orientations on topology structures are demonstrated.

The rest of work is organized as follows: The constitutive relationship of composite laminated plates is introduced in section 2. In section 3, the topology optimization model based on SIMP method is established, and the sensitivity analysis for the design of structure is presented. The topology design of wing rib is given in section 4, and the results are discussed. Finally, the conclusions are drawn.

2. Constitutive law for composite laminated plates

Composite laminated plates are formed by stacking a series of single layers in a certain lamination order, and their mechanical performance is mainly determined by the material properties, fiber orientations, layer thickness and laying order of the single layer. Fig.1 gives a structural chart of typical symmetric laminated plates. The total number of layers and thickness of laminated plates are denoted by N and h, respectively. The fiber angle and thickness of the k-th layer are defined as θ_k and t_k, respectively.

Based on the classical laminated plate theory, the constitutive equation of symmetrically laminated plates can be described as

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{21} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}, \qquad (1)$$

where $\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix}$ denote the internal force loads; $\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}$ denote the strains at the mid-plane; [A] represents the in-plane stiffness matrix and can be expressed as follows

$$\mathbf{A}=2\sum_{k=1}^{\frac{N}{2}} \overline{Q}^k \ (z_k - z_{k-1}), \qquad (2)$$

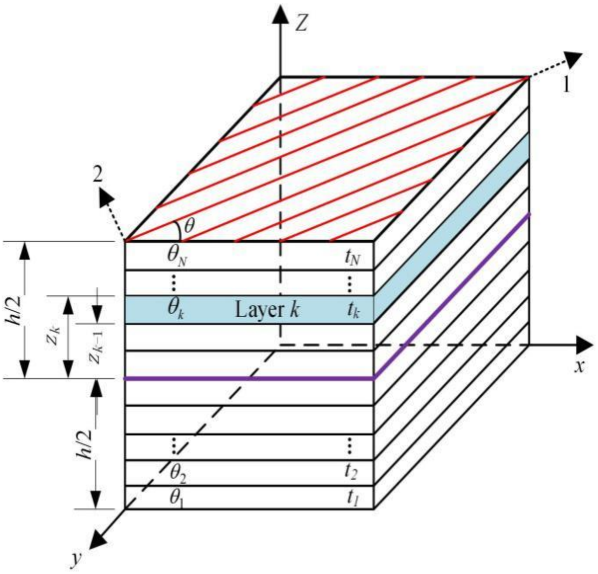


Fig. 1. Structure chart of symmetric composite laminated plates

where z_k and z_{k-1} are the upper and lower co-ordinates of the k-th layer, respectively;

$\overline{Q}^k$ is stiffness matrix of the k-th layer and can be written as

$$\overline{Q}^k = R^k \begin{bmatrix} \frac{E_1}{1-\nu_{12}\nu_{21}} & \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & \frac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \left(\mathbf{R^k}\right)^T, (3)$$

where, E_1, E_2 and G_{12} are the longitudinal modulus, transverse modulus and shear modulus refer to the material axes, respectively; ν_{12} and ν_{21} are the different Poisson's ratios.

The transformation matrix of the k-th layer with fiber orientation θk can be expressed as:

$$\mathbf{R^k} = \begin{bmatrix} \cos^2\theta^k & \sin^2\theta^k & -2\cos\theta^k\sin\theta^k \\ \sin^2\theta^k & \cos^2\theta^k & 2\cos\theta^k\sin\theta^k \\ \cos\theta^k\sin\theta^k & -\cos\theta^k\sin\theta^k & \cos^2\theta^k-\sin^2\theta^k \end{bmatrix}. \quad (4)$$

3. Topology design of wing rib with composite laminated plates

3.1. Topology optimization model based on SIMP method

Topology optimization is a method to find a reasonable material distribution in a given design area under certain boundary conditions. Here, the design objective is to minimize the compliance of structure, that is, to maximize the stiffness of structure by optimizing material distribution with the volume constraint. Based on the SIMP method, topology optimization model of wing rib with composite laminated plates can be expressed as follows:

$$\begin{aligned} &\text{find } \boldsymbol{\rho} = \left[\rho_1,..,\rho_e,..,\rho_{n_e}\right]^T, \\ &\min \quad f_0(\boldsymbol{\rho}) = \sum_{e=1}^{n_e} \mathbf{u}_e\mathbf{k}_e\mathbf{u}_e, \\ &\text{s.t.} \quad f_1(\rho) = \sum_{e=1}^{n_e} \rho_e\nu_e - gV_0 \le 0, \\ &\rho_e \in [\rho_{\min}, 1], \end{aligned} \quad (5)$$

where, ρ_e indicates the e-th element design variable with value between 0 and 1.

The e-th element is full of material if ρ_e=1, and the e-th element is void regions if $\rho_e=\rho_{\min}$ ($\rho_{\min}$ is a small value, e.g. 0.001), k_e is element stiffness matrix and can be obtained by $\mathbf{k}_e = \int \mathbf{B}^T\mathbf{A}_e\mathbf{B}\,d\nu_e$ (**B** is the strain-displacement matrix, $\mathbf{A}_e$ is the in-plane stiffness matrix of the e-th element), $\mathbf{u}_e$ denotes the nodal displacement vectors of the e-th element. The compliance of the structure is objective function represented by $f_0(\boldsymbol{\rho})$, and the constraint function is represented by $f_1(\boldsymbol{\rho})$. V_0 and ν_e are the initial volume of the design domain and e-th element volume, respectively. Parameter **g** is defined as volume fraction; n_e is the total element number of structure.

In the topology optimization of isotropic material, the Yong's modulus is usually penalized by the SIMP-method. For laminates, which are no longer isotropic, the in-plane stiffness matrix is penalized based on SIMP method

$$\mathbf{A}_e = \rho_e^p\mathbf{A}_0 = \rho_e^p\sum_{k=1}^{N} Q_{ij}^k t_k \qquad (i,j = 1,2,6), \qquad (6)$$

where $\mathbf{A}_0$ represents the in-plane stiffness matrix of solid element;

p is the penalization factor; P=5 is used in this paper.

3.2. Sensitivity analysis

The sensitivity analysis is a key step before implementing the topology optimization problem when using a gradient-based optimization algorithm. The sensitivity of objective function in Eq. (5) with respect to a change in design variable ρ_e can be expressed as:

$$\frac{\partial f_0}{\partial \rho_e} = -\mathbf{u}_e^T \frac{\partial k_e}{\partial \rho_e} \mathbf{u}_e = -\mathbf{u}_e^T \left(\int \mathbf{B}^T \frac{\partial \mathbf{A}_e}{\partial \rho_e} \mathbf{B} d\mathbf{v}_e \right) \mathbf{u}_e. \quad (7)$$

The derivation of $\mathbf{A}_e$ with respect to a change in design variable $\boldsymbol{\rho}_e$ can be expressed as:

$$\frac{\partial \mathbf{A}_e}{\partial \rho_e} = p \rho_e^{p-1} \mathbf{A}_0. \quad (8)$$

The sensitivity of the volume constraint function $f_1(\rho)$ with respect to design variables ρ_e can be directly derived as:

$$\frac{\partial f_1}{\partial \rho_e} = \frac{\partial}{\partial \rho_e} \left(\sum_{e=1}^{n} \rho_e v_e - g V_0 \right) = v_e. \quad (9)$$

In order to suppress numerical instabilities in the process of topology optimization, such as porous and checker-board phenomenon, a simple and effective sensitivity filter technique by modifying the element sensitivities is applied as [17]:

$$\frac{\partial \bar{f}_0}{\partial \rho_e} = \frac{1}{\rho_e \sum_{l \in N_i} H_l} \sum_{l \in N_i} H_l \rho_l \frac{\partial f_0}{\partial \rho_l}, \quad (10)$$

where, the weight factor H_l is written as:

$$H_l = \max(0, r_{min} - \mathrm{dist}(e, l)) \quad \{l \in N_l\}, \quad (11)$$

where, the dist(e, l) is defined as the distance between center of element e and center of element l, N_l is the set of elements l for which dist(e,l) is smaller than the filter radius r_{min}, $r_{min}=2$ is used in this paper.

3.3. Topology optimization flowchart

The topology optimization of wing rib with composite laminated plates is the iterative process repeatedly. At first, design domain and boundary conditions of structure are defined, and initialize the design variables $\boldsymbol{\rho}^0$. For each iteration, the in-plane stiffness matrix of e-th element $\mathbf{A}_e$ is built using Eq. (6). Then the objective function $f_0(\boldsymbol{\rho}^k)$ and volume constraint function $f_1(\boldsymbol{\rho}^k)$ are achieved by Eq. (4), the sensitivities of them are achieved by Eqs. (7) and (9), the index k is used to denote the number of iterations. Thereafter, the element sensitivities are modified by sensitivity filter technique according to Eq. (10). The optimized design points $\boldsymbol{\rho}^*$ can be obtained by adopting MMA algorithm (Fig. 2).

The result whether or not can be accepted by setting reasonable convergence conditions. If $\left| \max(\boldsymbol{\rho}^{k+1}) - \max(\boldsymbol{\rho}^k) \right| \le \varepsilon$, the optimal topology could be outputted, $\varepsilon=0.01$ is used in this paper. Otherwise, the design variables are updated repeatedly until convergence. The solution flowchart for topology optimization of wing rib with symmetric laminated plates is shown in Fig. 2.

4. Optimization results and analysis

In the design of aircraft structure, how to obtain a lighter structure is always a challenge and goal for engineering designers. The development of topology optimization offers an innovation for lightweight design of the aircraft. In this study, the wing rib under torsion is optimized by the topology optimization method. Fig.3 presents the initial structure of the wing rib given by Bruhn [18]. For simplicity, the wing rib's shape is approximated by a rectangular domain of size 0.8 m×0.3 m, and the original loads are approximated by a shear load on each edge, as seen from Fig.4. The magnitude of the load is converted from English to metric units. The flanges and beads are all neglected. The design domain is discretized with 80×30 four-node quadrilateral elements. Unidirectional AS4/9773 carbon fiber reinforced epoxy resin is selected as single layer material, the material constants are give as follows [19]: $E_1=129.8$ GPa, $E_2=E_3=9.24$ GPa, $v_{23}=0.1$, $v_{12}=v_{13}=0.36$, $G_{23}=2$ GPa, $G_{12}=G_{13}=5.1$ GPa.

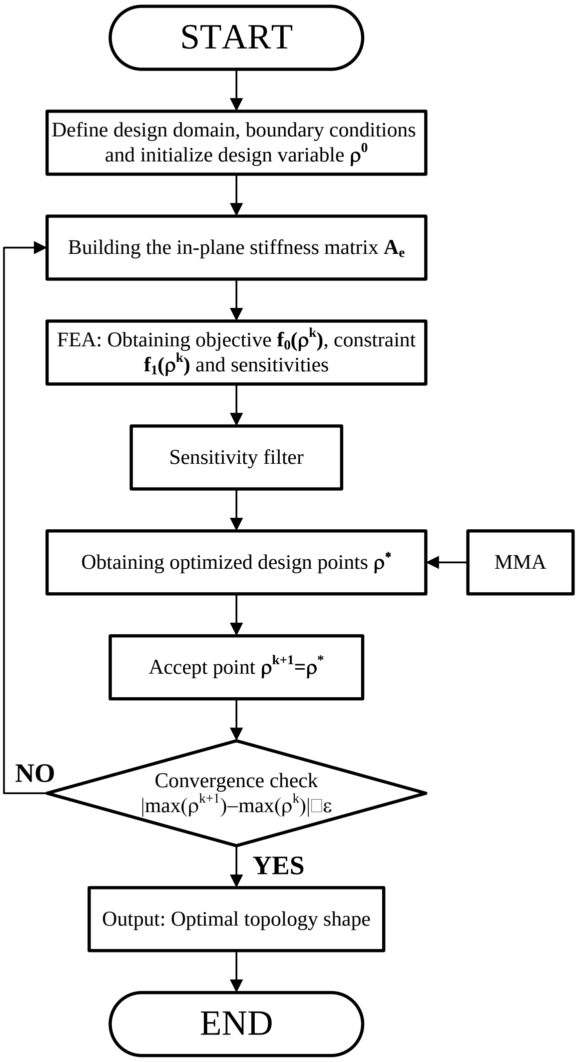


Fig. 2. Solution flowchart of topology optimization

Assume that the wing rib is composed of 16 equal thickness single layers and the total thickness is 4 mm.

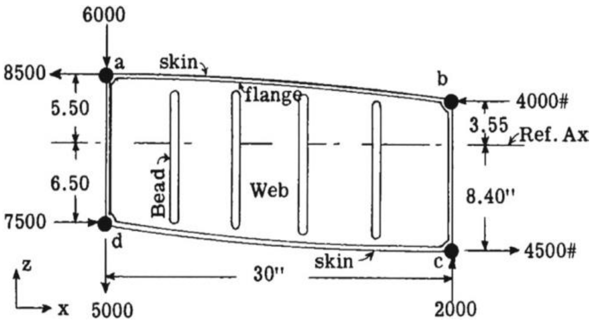


Fig. 3. Original wing rib load case [18], loads in lb

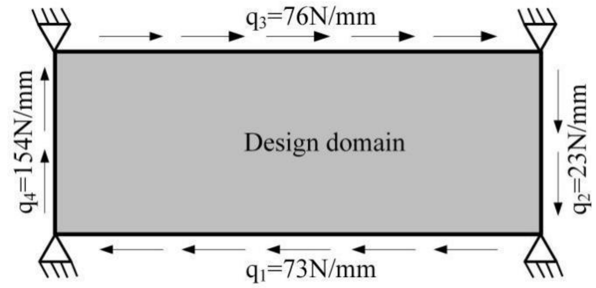


Fig.4. Design domain and boundary conditions of simplified wing rib

As we all know, the mechanical properties of composite laminated plates mainly depend on the fiber directions. In order to study the influences of fiber orientations on topology structures, different topology structures of the wing rib can be obtained with different fiber orientations based on the model described by Eq. (5). The optimized topologies of wing rib with specific fiber orientation sand 50% volume constraint are shown in Fig. 5. The image of Fig. 5, a is those of the isotropic material (aluminum alloy). Fig. 5, b … Fig. 5, d shows the images of the laminated composite plates under different layer sequences: $[0/45/90/45]_{2s}$, $[45/-45/90/-45]_{2s}$ and $[0/45/-45/45]_{2s}$. Comparing the topology results of isotropic material (see Fig. 5, a) with the results of specific fiber orientations (see Fig. 5, b … Fig. 5, d), it can be seen that the topology shape is changed greatly when using composite laminated plates. As seen in Fig. 5, b … Fig. 5, d, the topology shapes of the wing rib with composite laminated plates are strongly dependent on layer sequences.

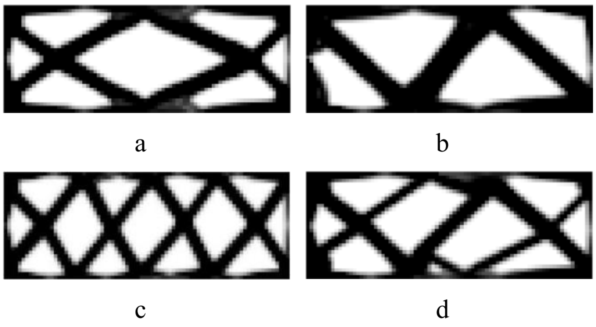

a b
c d

Fig. 5. Images of topology optimization results of wing rib with isotropic material and specific fiber directions: a – Aluminum alloy; b – $[0/45/90/45]_{2s}$; c – $[45/-45/90/-45]_{2s}$; d – $[0/45/-45/45]_{2s}$

The iteration curves of the objective function are exhibited in Fig. 6. From the Fig. 6, the fiber orientations have a great influence on the stiffness of optimized structure. These results indicate that the optimization process has stable convergence, and the stiffness of the wing rib can be improved efficiency after topology optimization design.

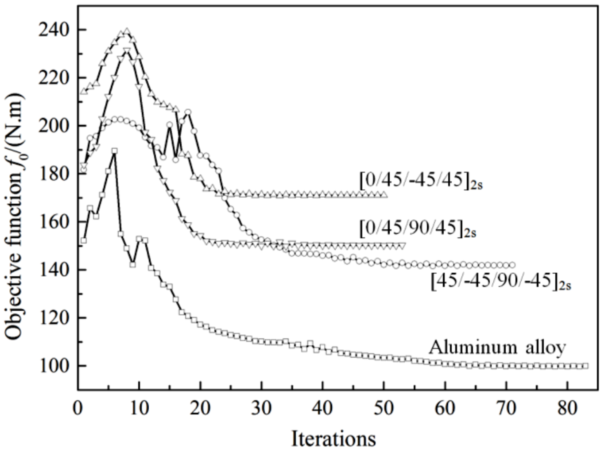


Fig. 6. Objective curves of wing rib with isotropic material and specific fiber directions

In order to demonstrate the effectiveness of the topology optimization method, the anti-deforming capability needs to be compared between optimized structure and un-optimized structure. The layer sequences are defined as: [45/-45/90/0]$_{2s}$. The target volume fractions of the structure set to be 60%.

The resulting topology of the wing rib is shown in Fig. 7, and the iteration curves of the objective function and volume fraction are exhibited in Fig. 8. It can clearly be seen that stable values of objective function and the volume fraction are 111.5 N/mm and 60 %, respectively.

In general, the topology result cannot be directly used as the final design of the structure. The topology shape needs to be remodeled with consideration of the relevant technological restrictions. An available engineering structure after optimized is shown in Fig. 9. The practice of using large holes to reduce weight is common in most traditionally manufactured aircraft due to its simplicity. One of un-optimized traditional designs of the wing rib is shown in Fig. 10. The rate of material removal is 35% for both structures.

By applying the ANSYS analytical software, the deformation of both structures under the same loads and constraints are analyzed. In simulation analysis, the shell99 element is selected. Before meshed by free method, the two short-sides and two long sides of structure are divided into 30 equal parts and 80 equal parts, respectively.

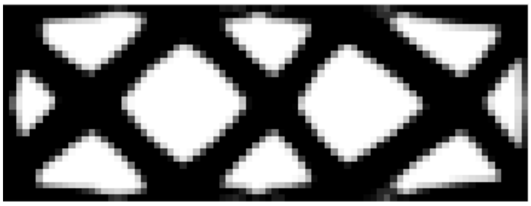


Fig. 7. Topology result of simplified wing rib

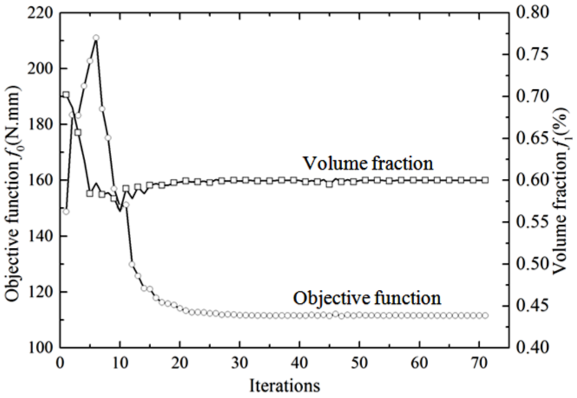


Fig. 8. Iteration curves of the objective function and volume fraction for simplified wing rib

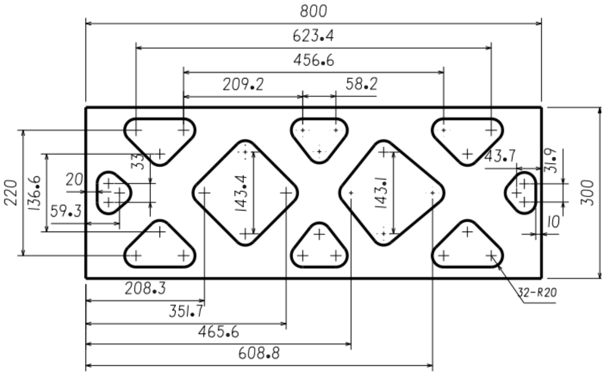


Fig. 9. Optimized structure of the wing rib (unit: mm)

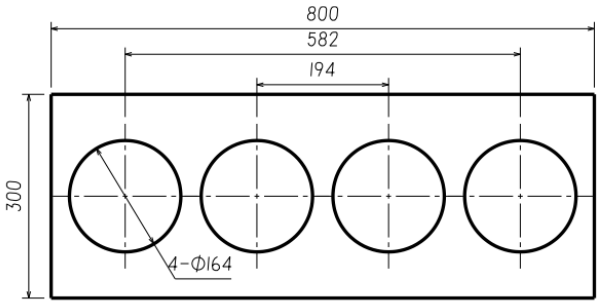
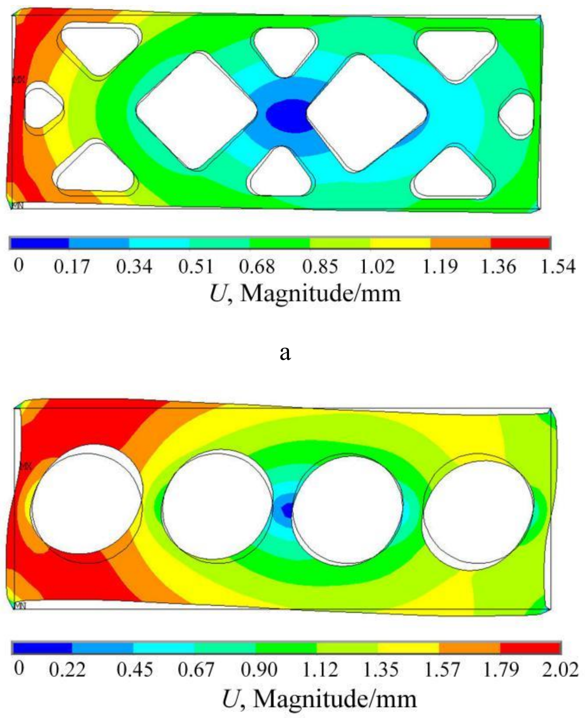


Fig. 10. Un-optimized structure of the wing rib (unit: mm)

The elements' number of the optimized and un-optimized structures are 1650 and 1327, respectively. The finite element simulation results of optimized and un-optimized structures are shown in Fig. 11, a and Fig. 11, b, respectively. The simulation result shows that the maximum deformation value of optimized and un-optimized structure are 1.57 mm and 2.02 mm, respectively. Therefore, the deformation can be reduced by 22.3 % with the help of topology optimization technology.



a

b

Fig. 11. Finite element simulation results of wing rib, scale factor is 10:
a – Optimized structure; b – Un-optimized structure

5. Conclusions

In this study, the approach for designing wing rib with symmetric laminated plates is presented based on topology optimization. The MMA algorithm and sensitivity filtering technique are adopted to solve the optimization problem and ensure the existence of solutions. The topology results show that the fiber orientations of laminated plates have significant influence on topology shapes and stiffness of structure. Taking the topology structure obtained using the fiber layer sequences [45/-45/90/0]2s as an example, the anti-deforming capability is compared between optimized and un-optimized structures. The results show that the established method is effective and rational for the design of aircraft structures. Under the condition of the same material removals, the optimized structure of wing rib can decrease 22.3% deformations.

Acknowledgements

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References (GOST 7.1:2006)

1. Banichuk, N. V. Minimum-weight design of multi-purpose cylindrical bars [Text] / N. V. Banichuk, B. L. Karihaloo // International Journal of solids and Structures. – 1976. – Vol. 12. – No. 4. – P. 267–273.

2. Week, M. An efficient technique in shape optimization [Text] / M. Week, P. Stelnke // Journal of structural mechanics. – 1983. – Vol. 11. – No. 4. – P. 433–449.

3. Plocher, J. Review on design and structural optimisation in additive manufacturing: towards next-generation lightweight structures [Text] / J. Plocher, A. Panesar // Materials & Design. – 2019. – Vol. 183. – Article Id: 108164.

4. Bendsøe, M. P. Topology optimization-theory, methods, and applications [Text] / M. P. Bendsøe, O. Sigmund. – Berlin : Springer-Verlag, 2004. – 381 p.

5. Safonov, A. A. 3D topology optimization of continuous fiber-reinforced structures via natural *evolution method [Text] / A. A. Safonov // Composite Structures. – 2019. – Vol. 215. – P. 289–297.*

6. Zhu, J.-H. Topology optimization in aircraft and aerospace structures design [Text] / J.-H. Zhu, W.-H. Zhang, L. Xia // Archives of Computational Methods in Engineering. – 2016. – Vol. 23, No. 4. – P. 595–622.

7. López, C. The relevance of reliability-based topology optimization in early design stages of aircraft structures [Text] / C. López, A. Baldomir, S. Hernández // Struct Multidisc Optim. – 2018. – Vol. 57. – P. 417–439.

8. Wu, X. H. Application of Optimization Technology in Boeing 787 Design [Text] / X. H. Wu, and X. H. Hong // Digital Design and Manufacturing Technology for Large Aircraft. – 2008. – Vol. 14. – P. 51-52.

9. Zhu, J. Topology Optimization in Aircraft and Aerospace Structures Design [Text] / J. Zhu, W. Zhang, & L. Xia // Arch Computat. Methods Eng. – 2016. – Vol. 23. – P. 595–622.

10. Liu, J. Current and future trends in topology optimization for additive manufacturing [Text] / J. Liu, A. T. Gaynor, S. Chen // Struct Multidisc Optim. – 2018. – Vol. 57. – P. 2457–2483.

11. Topology optimization of compliant adaptive wing leading edge with composite materials [Text] / X. Tong, W. Ge, C. Sun, et al. // Chinese Journal of Aeronautics. – 2014. – Vol. 27, No. 6. – P. 1488–1494.

12. Topology design and analysis of compliant mechanisms with composite laminated plates [Text] / X. Tong, W. Ge, Y. Zhang, et al. // Journal of Mechanical Science and Technology. – 2019. – Vol. 33, No. 2. – P. 613–620.

13. Boddeti, N. Optimal design and manufacture of variable stiffness laminated continuous fibre-reinforced composites [Text] / N. Boddeti, Y. Tang, K. Maute et al. // Sci. Rep. – 2020. – Vol. 10. – Article Id: 16507.

14. Gao, T. A bi-value coding parameterization scheme for the discrete optimal orientation design of the composite laminate [Text] / T. Gao, W. Zhang and P. Duysinx // International Journal for Numerical Methods in Engineering. – 2012. – Vol. 91, No. 1. – P. 98–114.

15. Bendsøe, M. P. Material interpolation schemes in topology optimization [Text] / M. P. Bendsøe and O. Sigmund // Archive of applied mechanics. – 1999. – Vol. 69, No. 9-10. – P. 635–654.

16. Multiscale topology optimization for minimizing frequency responses of cellular composites with connectable graded microstructures [Text] / Yan Zhang, Mi Xiao, Liang Gao, Jie Gao, Hao Li // Mechanical Systems and Signal Processing. – 2020. – Vol. 135. – Article Id: 106369.

17. Design of compliant mechanisms using continuum topology optimization: A review [Text] / Benliang Zhu, Xianmin Zhang, Hongchuan Zhang, Junwen Liang // Mechanism and Machine Theory. – 2020. – Vol. 143. – Article Id: 103622.

18. Bruhn, E. F. Analysis and design of flight vehicle structures [Text] / E. F. Bruhn. – New York : Tri-State *Offset Company*, 1973. – 996 p.

19. Venkatachari, A. Variable stiffness laminated composite shells — Free vibration characteristics based on higher-order structural theory. [Text] / A. Venkatachari, S. Natarajan, M. Ganapathi // Compos. Struct. – 2018. – Vol. 188. – P. 407–414.

References (BSI)

1. Banichuk, N. V., Karihaloo B. L. Minimum-weight design of multi-purpose cylindrical bars. *International Journal of solids and Structures*, 1976, vol. 12, no. 4, pp. 267-273.

2. Week, M., Stelnke, P. An efficient technique in shape optimization. *Journal of structural mechanic*, 1983, vol. 11, no. 4, pp. 433-449.

3. Plocher, J., Panesar, A. Review on design and structural optimisation in additive manufacturing: towards next-generation lightweight structures. *Materials & Design*, 2019, vol. 183, article id: 108164.

4. Bendsøe, M. P., Sigmund, O. *Topology optimization-theory, methods, and applications*. Berlin, Springer-Verlag Publ., 2004. 381 p.

5. Safonov, A. A. 3D topology optimization of continuous fiber-reinforced structures via natural evolution method. *Composite Structures*, 2019, vol. 215, pp. 289-297.

6. Zhu, J.-H., Zhang, W.-H. and Xia, L. Topology optimization in aircraft and aerospace structures design.

Archives of Computational Methods in Engineering, 2016, vol. 23, no. 4, pp. 595-622.

7. López, C., Baldomir, A., Hernández, S. The relevance of reliability-based topology optimization in early design stages of aircraft structures. *Struct Multidisc Optim.*, 2018, vol. 57, pp. 417–439.

8. Wu, X. H., and Hong, X. H. Application of Optimization Technology in Boeing 787 Design. *Digital Design and Manufacturing Technology for Large Aircraft*, 2008, vol. 14, pp. 51-52.

9. Zhu, J., Zhang, W., & Xia, L. Topology Optimization in Aircraft and Aerospace Structures Design. *Arch Computat. Methods Eng*, 2016, vol. 23, pp. 595–622.

10. Liu, J., Gaynor, A. T., Chen, S. Current and future trends in topology optimization for additive manufacturing. *Struct Multidisc Optim*, 2018, vol. 57. pp. 2457–2483.

11. Tong, X., Ge, W., Sun, C., et al. Topology optimization of compliant adaptive wing leading edge with composite materials. *Chinese Journal of Aeronautics*, 2014, vol. 27, no. 6, pp. 1488-1494.

12. Tong, X., Ge, W., Zhang, Y., et al. Topology design and analysis of compliant mechanisms with composite laminated plates. *Journal of Mechanical Science and Technology*, 2019, vol. 33, no. 2, pp. 613-620.

13. Boddeti, N., Tang, Y., Maute, K., et al. Optimal design and manufacture of variable stiffness laminated continuous fibre-reinforced composites. *Sci. Rep.*, 2020, vol. 10, article id: 16507.

14. Gao, T., Zhang, W., and Duysinx, P. A bi-value coding parameterization scheme for the discrete optimal orientation design of the composite laminate. *International Journal for Numerical Methods in Engineering*, 2012, vol. 91, no. 1, pp. 98-114.

15. Bendsøe, M. P. and Sigmund, O. Material interpolation schemes in topology optimization. *Archive of applied mechanics*, 1999, vol. 69, no. 9-10, pp. 635-654.

16. Zhang, Y., Xiao, M., Gao, L., et al. Multiscale topology optimization for minimizing frequency responses of cellular composites with connectable graded microstructures. *Mechanical Systems and Signal Processing*, 2020, vol. 135, article id: 106369.

17. Zhu, B., Zhang, X., Zhang, H. Design of compliant mechanisms using continuum topology optimization: A review. *Mechanism and Machine Theory*, 2020, vol. 143, article id: 103622.

18. Bruhn, E. F. *Analysis and design of flight vehicle structures.* New York, Tri-State Offset Company Publ., 1973. 996 p.

19. Venkatachari, A., Natarajan, S., Ganapathi, M. Variable stiffness laminated composite shells-Free vibration characteristics based on higher-order structural theory. *Compos. Struct.*, 2018, vol. 188, pp. 407-414.

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ТОПОЛОГІЧНЕ ПРОЕКТУВАННЯ ТА АНАЛІЗ КОМПОЗИТНОЇ НЕРВЮРИ КРИЛА

Чжен Ху, О. О. Вамболь

В останні десятиліття в аерокосмічній галузі широко застосовуються композитні конструкції, проте на початку 21 століття спостерігається стрімке їх зростання. Найбільші компанії в аерокосмічній галузі нарощують обсяги застосування композитів (КМ) в конструкціях, і на сьогоднішній день обсяги КМ сягає 50%. Різні елементи літальних апаратів і навіть високонавантажені конструкції, такі як лонжерони, нервюри, обшивка тощо, в даний час виготовляються з композитів. В першу чергу, це пов'язано з можливістю значно знизити масу конструкції і виробничі витрати. Передові технології інженерного програмного забезпечення дозволяють вирішувати найскладніші задачі. Одним з основних напрямків досліджень композитів є оптимізація структури композиту за рахунок поліпшення відносної міцності та відносної жорсткості КМ, а також підвищення ефективності виробничих процесів. Існує безліч методів оптимізації структури, але в даний час топологічна оптимізація є найбільш концептуальним і перспективним методом. Основна мета статті - проаналізувати та оцінити підхід до проектування нервюр крила з симетричними шаруватими пластинами з різною орієнтацією волокон на основі топологічної оптимізації. Для цього вирішувалися наступні задачі: по-перше, була визначена модель топологічної оптимізації, яка базувалася на максимальної жорсткості з заданими обмеженнями обсягу. Наступний крок - була проведена оптимізація за допомогою методу твердотільного ізотропного матеріалу з застосуванням моделі штрафних функцій (SIMP) і техніки фільтрації, в результаті чого були отримані топологічні структури нервюр крила з різною орієнтацією волокон. Топологічна структура і жорсткість нервюри крила залежать від орієнтації волокон. Нарешті, був проведений аналіз можливого згладжування нервюр крила багатошарової композитної структури. Згладжування було реалізовано за допомогою програмного продукту ANSYS, який підтвердив анти-деформуючу здатність топологічної конструкції і продемонстрував можливість розробки нервюр крила.

Ключові слова: топологічна оптимізація; шаруватий композит; орієнтація волокна; нервюра крила.

ТОПОЛОГИЧЕСКОЕ ПРОЕКТИРОВАНИЕ И АНАЛИЗ КОМПОЗИТНОЙ НЕРВЮРЫ КРЫЛА

Чжен Ху, А. А. Вамболь

В последние десятилетия в аэрокосмической отрасли широко применяются композитные конструкции, однако в начале 21 века наблюдается стремительный их рост. Крупнейшие компании в аэрокосмической отрасли наращивают объемы применения композитов (КМ) в конструкциях, и на сегодняшний день объемы КМ достигает 50 %. Различные элементы летательных аппаратов и даже высоконагруженные конструкции, такие как лонжероны, нервюры, обшивка и т. д., в настоящее время изготавливаются из композитов. В первую очередь, это связано с возможностью значительно снизить вес конструкции и производственные затраты. Передовые технологии инженерного программного обеспечения позволяют решать самые сложные задачи. Одним из основных направлений исследований композитов является оптимизация структуры композита за счет улучшения относительной прочности и относительной жесткости КМ, а также повышения эффективности производственных процессов. Существует множество методов оптимизации структуры, но в настоящее время топологическая оптимизация является наиболее концептуальным и перспективным методом. Основная цель статьи - проанализировать и оценить подход к проектированию нервюр крыла с симметричными слоистыми пластинами с различной ориентацией волокон на основе топологической оптимизации. Для этого решались следующие задачи: во-первых, определялась топологическая оптимизационная модель. Эта модель была основана на максимальной жесткости с заданным ограничением объема. Следующий шаг – была проведена оптимизация при помощи метода твердотельного изотропного материала с применением модели штрафных функций (SIMP) и техники фильтрации, в результате чего были получены топологические структуры нервюр крыла с различной ориентацией волокон. Топологическая структура и жесткость нервюры крыла зависят от ориентации волокон. Наконец, был проведен анализ возможного сглаживания нервюр крыла многослойной композитной структуры. Сглаживание было реализовано с помощью программного продукта ANSYS, который подтвердил анти-деформирующую способность топологической конструкции и продемонстрировал возможность разработки нервюр крыла. Результат исследований показывает, что максимальная деформация оптимизированной конструкции составляет 1,57 мм, тогда как максимальная деформация неоптимизированной конструкции составляет

2,02 мм. Использование топологической оптимизации позволяет снизить уровень деформации более чем на 20 %.

Ключевые слова: топологическая оптимизация; слоистые композиты; ориентация волокна; нервюра крыла.

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