Research on the Composite Structure Optimization Method Based on Manufacturing Constraints

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Abstract. An optimization strategy is presented for large composite structure based on manufacturing constraints and genetic algorithm. First, on the basis of region division and key region defined, both angle and length design variables for each ply are introduced to make laminate thickness and stacking sequence be optimized simultaneously, also considering laminate ply continuity. Finally, a composite wing is optimized using the current methodology. The result shows that the optimization method can obtain optimum design satisfying manufacturing constraints and weight reduction for large composite structure.

Introduction

Due to their outstanding mechanical properties and design ability, composite materials are increasingly applied in aviation and aerospace fields, going through a process being used as secondary weight-bearing components and then major weight-bearing components and a stage of replacement design to clean sheet design. The quantity and location of composite materials being used has become an important index to measure if an aircraft structure is advanced or not [1]. The demand on using composite structures promotes the development of structural design and optimization design of composite structures. Domestic and foreign scholars have completed a lot of researches into the optimization design of composite structures, presenting multi-step optimization method [2-5] for stacking thickness and stacking sequence classification and genetic algorithm-based stacking sequence optimization method [6-9].

For large structures such as aircraft wings and fuselage, to reduce their weight as much as possible, sub-region division and optimization shall be conducted based on load distribution (E.g., the, the roots of wings are heavily loaded but the tips of wings are lightly loaded, so the wings could be subject to sub-region division along the span direction). However, current works usually conduct separate optimization of sub-regions the result of which could not ensure the fiber continuity between adjacent regions. Discontinued fiber would not only result in concentrated stress in connection area of the region but would also lead to increased number of connecting parts or even non-feasibility in manufacturing process. When conducting lamination design for composite materials with the consideration of the technological requirements, continuity constraints shall be taken into account to guarantee lamination continuity in certain number between adjacent regions. Relevant foreign works have studied fiber continuity optimization models [10-14]. Wherein, Liu [11] uses the ratio of the number of continued lamination layers between adjacent regions to the number of overall layers to measure fiber continuity. Adams obtains the optimization result of composite
materials with fiber continuity through distributed genetic algorithm and presents two optimization models based on fiber continuity.

To address the problems above, this paper presents a genetic algorithm-based optimization method which could optimize the stacking thickness and stacking sequence at the same time and which could guarantee the fiber continuity between adjacent regions.

**Fiber Continuity**

Large structures made of composite materials could be subject to optimized region division according to engineering experience and loading analysis. Without considering abrupt change of load, these regions have a thickest one, i.e., the critical region, and the thickness decreases progressively along the critical region to further regions. As is shown in Fig. 1, the Sub-Region 1 is the critical region of the whole panel, each single layer of the composite material will start from Sub-Region 1 and extend to other regions. Fig. 2 shows the status of fiber continuity in the thick region (Lamination A) and thin region (Lamination B). The stacking layer in the thin region could be extended to the thin region, or may break at the connection points in the region. For example, P1, P3, P4 and P6 of Lamination A extend to Lamination B, while P2 and P5 break at the connection points.

![Figure 1. Region division and key region of a panel.](image1)

![Figure 2. Laminate plies between adjacent regions.](image2)

Two variables (angle variable $\theta$ and length variable $L$) are introduced for each single layer. The value of $\theta$ at 1, 2, 3 and 4 represent the angles of single stacking layers at 0, 45, -45 and 90 degrees, respectively. Length variable $L$ represents the number of covered regions. Not only could this method ensure that the thickness and stacking sequence of the stacking layers of composite materials be optimized respectively in one time, but it could also guarantee that the technological requirements of composite materials be met and fibers could continue as much as possible to reduce the concentration of stress and the difficulty of processing.

**Optimization Model**

This paper conducts optimization design of aircraft wings made of composite materials as is shown in Fig.3. The objects of optimized design include the stacking thickness and sequence for the top skin, bottom skin, front spar and rear spar.
Objective Function

\[ \min W = W_0 + \sum_{i=1}^{n} \rho h S_i \]  

Wherein: \( W_0 \) is the weight of components not subject to optimized design, including the ribs, stringers and spar booms; \( \rho \) and \( h \) respectively represent the thickness of the composite material and the single-layer thickness; \( n \) is the number of the largest stacking layers; \( S_i \) is the area of each single layer, representing the area each single layer covers.

Design Variables

\( \theta \), the stacking layer of each single layer, and \( L \), the length of the single layer, are used as the design variables. \( L \) represents the number of regions covered by the single layer. In other words, through each single layer’s value of \( L \), \( n \) (number of stacking layers of the objective function) and \( S \) (the area of the single layer), could be concluded.

Restrictive Conditions

(1) Rigidity Restraint: including the restraint on maximum displacement of the wingtips and restriction on the torsion angle.

(2) Strain restriction: \( \varepsilon \leq [\varepsilon]_{\text{allow}} \). The strain (positive strain and shear strain) on the top and bottom surfaces of the laminated sheet are used as the working strain which would be calibrated and checked as allowed strain for the design.

(3) Stability restraint: none of the components are allowed to show local bending or overall bending.

(4) Processing requirements on the stacking layer: stack layers in a symmetrical manner; to increase the damage tolerance and the ability to resist impact, the outermost surface shall have at least one group of \( \pm 45 \) stacking layers extended from the root region to the tip region; to reduce the stress between layers, the single layer of the same stacking layer shall not concentrate together too much and the number of layers shall not exceed 4.

Optimization algorithm

The integer-coded genetic algorithm is used. For example, Code \([1 \, 2 \, 4 \, 3 \mid 0 \, 3 \, 2 \, 8]\) means that: the 0-degree stacking layer does not exist; the 45-degree stacking layer covers the first 3 regions; the 90-degree stacking layer covers the first 2 regions; the -45-degree stacking layer covers the first 8 regions.
The elitist preservation mechanism is introduced for the genetic algorithm. Upon selection, the offsprings of the individuals involved in reproduction compete with their parent individuals in the mating pool to produce the next generation, which is helpful to preserve elite individuals and further control the selection pressure and the speed of balanced evolution and avoid the phenomenon of “pre-maturity” and stagnation.

Example

The straight aircraft wing box made of composite materials has an extension length of 4.4m and a chord length of 0.6m. The finite element model includes two beams, 9 ribs and 8 stringers. First of all, the optimization objectives are divided into 8 sections along the span direction according to the position of the ribs, each section consisting of 4 thin plates, as shown in Fig.4 and Fig. 5. They are respectively the top skin, bottom skin, front spar and rear spar, all being symmetrical balanced stacking layers. See Table 1 for the properties of single-layer materials.

![Figure 4. Region division along span wise of wing box.](image1)

![Figure 5. Geometry of wing cross section.](image2)

| Table 1. Material property. |
|-----------------------------|
| $E_1$ | $E_2$ | $G_{12}$ | $v_{12}$ | $\rho$ | $t$ |
| 135GPa | 8.8GPa | 4.47GPa | 0.3 | 1450kg/m$^3$ | 0.12m |

Conduct optimization by using the optimization strategy proposed in this paper. Firstly, it can be judged that for both the upper and bottom skins and front and rear spars, the root region is the thickest and the thickness decreases along the span direction. Therefore, No.1 Sub-region is selected as the critical region to establish the optimization model. For all components, the initial stacking layers are $[0_0/45_0/-45_0/90_0]$, and the total number is 80 layers. As the stacking layers are symmetrical, the number of design variables is $4 \times (40 + 40) = 320$. The parameter setting for the genetic algorithm is as below: the population size is 800; the number of evolution generations is 500; the crossover probability is 0.9; the mutation rate is 0.01. Upon optimization, the weight is reduced to 91.8kg from the original value of 117.1kg.
For both the upper and bottom skins and front and rear spars, No. 1 Sub-region is the thickest. In addition to reduced weight, the processing requirement on the continuity of the stacking layers is met to the maximum extent, posing further guiding significance to engineering applications. Limited by the length of the paper, Table 2 gives the optimal solution for detailed stacking layers of the top skin.

Table 2. Stacking sequence of top skin regions.

| Region | Stacking sequences                                                                 | Number of plies |
|--------|------------------------------------------------------------------------------------|-----------------|
| 1      | 24 2 2 3 4 3 s[45/-45/0/45/90/45/0,/-45/90/-45/0/45/0,/-45/0/45,0]                | 60              |
| 2      | 24 2 2 3 2 2 s[45/-45/0/45/90/45/0,/-45/0/0/45,0/-45/0]                        | 48              |
| 3      | 24 2 4 s[45/-45/0/90/45/0,/-45/0,/-45/0,0/-45/0]                       | 38              |
| 4      | 24 2 s[45/-45/0/45/0,/-45/0/-45/0,0]                                        | 30              |
| 5      | 23 2 3 s[45/-45/0/90/0,/-45/0,/-45/0,0]                                   | 28              |
| 6      | 2 3 s[45/-45/0/90/0,/-45/0,/-45/0,0]                                     | 26              |
| 7      | 2 2 s[45/-45/0/45/0,/-45/0]                                               | 22              |
| 8      | 2 s[45/-45/0/45/0,/-45/0]                                                  | 16              |

Conclusions

On the basis of dividing and identifying critical regions, by introducing the variables of angle and length to each single layer, this paper tries to optimize stacking thickness and stacking sequence at the same time to guarantee technological requirements such as fiber continuity. In addition, this paper verifies the validity of the method through the example of wing box optimization.

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