OPTIMIZATION DESIGN OF COMPOSITE WING WITH MULTIPLE LOAD CASES AND LARGE SCALE DESIGN VARIABLES

Rui Zhang*,Hai Du*, Degang Cui**
*** Flight Physics Research Center, Chinese Aeronautical Establishment（CAE）,Beijing, China**
**** Science and Technology Committee, AVIC, Beijing, China**

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Abstract

Wing is the main part of aircraft for lift. It bears not only the lift but also the concentrated loads from the engine, landing gear and other devices. The optimization of wing is to design a structure that meets all the demands for using with less structure weight. This paper introduces a method for the optimization design of composite wing with multiple load cases and large scale design variables. An optimization process is built to carry out this method ,and finally it is proved by the optimization design of a wing skin with 10^5 design variables and 30 load cases.

1 General Introduction

The application of composite material brings the structure design new development and become an important feature of the advancement aircraft. For the anisotropic property, the composite structure's stiffness on different direction can be designed respectively [1].

Nowadays aircraft design has become into a stable development. Each discipline resorts to accurate design and cooperated design to obtain better performance. Accurate design and multidisciplinary optimization design both need large scale design variables. The amount of variables could be more than several thousand and the multiple load cases also increase the number of design variables [2][3].

2 Method and Process

2.1 Principle of Optimization

The design variables in composite structure optimization usually are relevant parameters of skin laminate that are ply direction, thickness and ply percentages.

General optimization usually takes weight as the objective function and strain as constraint [4]. In this research, structure size starts from the minimum value and increases gradually .The increment of weight each step is constant. Every optimization cycle is to find the best sequence formation of certain material (ply orientation, thickness) in which the strength is strengthened most.

The allowable strains are used to establish the objective function. At beginning, the working strain is greater than the allowable strains. With the optimization process, the working strain is getting close to the allowable strains, and finally lower than them. Therefore, there is need to build an objective function based on allowable strain on each direction.

Formula one is the objective function with allowable strain, which uses the distance between design point and the worst feasible point. This function could reflect the distance between the working strain and the allowable strain, but it can't make strain in each direction descend simultaneously which may result in the objective function decreasing in only one direction and the value's vibration.

$$f_1 = \begin{cases} \sqrt{\sum_{i=x,y,xy}(\varepsilon_i - \varepsilon_i^a)^2}, & \varepsilon_i > \varepsilon_i^a \\ 0, & \varepsilon_i \le \varepsilon_i^a \end{cases} \quad (1)$$

ε_i is the working strain of direction x,y,and xy.

ε_i^a is the allowable strain of direction x, y, and xy.

f_1 is the objective function.

For most load cases, the skin sustains the bending moment, so the tension and compression of objective function are much higher than the shear strain that the value of objective function decreases along the tension/compression. However, for some load case, the wing will sustain some inner plane loads and shear strain becomes the main factor. So the optimization needs to carry out iteratively with different load case.

2.2 Process of Optimization

In order to enlarge the design space and realize the fine design, each piece of skin divided by finite element will be dealt with independently and the ply direction ranges from 90 degree to minus 90 degree with an integer increment. For example, the number of finite elements of skin in wing box is 200. In each optimization step, the possible combination of design variable will reach to the magnitude of 10^{62}, which makes it harder to find the optimal design and when considering multiple load cases, large scale design variables optimization becomes more difficult.

So as to settle the problem stated above, this paper puts forward an optimized design process depicted in Fig. 2. First of all, the severity of the model under all the load cases is analyzed. The most dangerous load case is selected as the basic load case to optimize. When it is optimized to some extent, the current model under all the load cases is checked. For those load cases that satisfy the allowable strains, the corresponding load case is skipped in the following optimization. For those that fail, the optimization will carry out with the current model until the entire model is safe under all the load cases.

In this process, the double cycle optimization based on genetic algorithm (GA [5]) reduces the design variable to an achievable magnitude through sectional dealing with the variables. The double cycle optimization is showed in figure 3. The outer loop is the ranking of design element sensitivities. The inner loop is the GA optimization referring to the ranking result of all the design elements [6]. When the optimization finishes a cycle of the outer process in fig 2, it is called a step. For the inner process, it is called a loop.

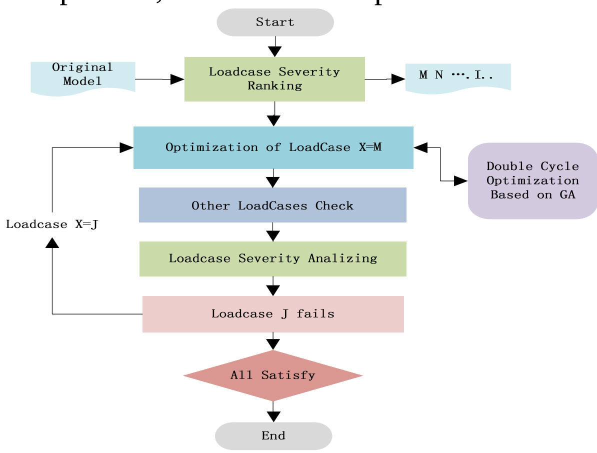

Fig. 1 The Optimization Process

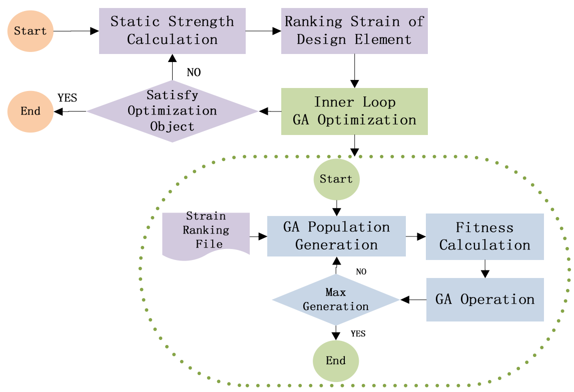

Fig. 2 The Double Cycle Optimization

The process showed in Fig. 2 and Fig. 3 is executed on SAMOS (Sensitivity Analysis Based Multi-discipline Optimization System) [7][8]. This paper will not introduce the function of this system.

2.3 Post Process of Optimization

The design variable is optimized separately without considering the manufacture constraints, so that the result may not fulfill the demands of manufacturing. The post processor is needed, which includes the equivalence design of ply orientation and fitting of element ply thickness [9].

After finishing the optimization design, the initial model for post process is prepared. The first step is to change the ply direction of each element to regular ply direction ,that are 0°，45°，-45° and 90°。 At the same time, the number of layers is round to integer and the thickness of each ply is the regular thickness. The three direction stiffness equivalent design is for single laminate. For the independence of each element, the thickness along the chord and the span become unsmooth. Therefore, it is needed to fitting the discrete thickness of design element.

2.3.1 Three direction stiffness equivalent design

Longitudinal, transverse, shear stiffness are the basic property of laminate. It has proved that the thickness of laminate keeps constant with the changing of ply orientations when the three direction stiffness is definite [10].

The inner stiffness coefficients are calculated with formula 2.

$$A_{ij} = \sum_{k=1}^{N} t_k \left(\overline{Q}_{ij}\right)_k \qquad (2)$$

i=1,2,6; j=1,2,6

In formula 2, N stands for the layers number of laminate, t_k is thickness of single layer and $\overline{Q}_{ij}$ for translated reduced stiffnesses. *A11*，*A12*，*A22*，*A66* are the in-plane, tensile stiffness coefficient.

$\overline{Q}_{ij}$ change with ply direction, A_{ij}have nothing to do with stacking sequence and are determined only by ply percentages. Therefore, considering a laminate compose with ply α，β，γ, A_{ij} can be stated in those forms ：

$$A_{ij} = \left(N_\alpha \overline{Q}_{ij,\alpha} + N_\beta \overline{Q}_{ij,\beta} + N_\gamma \overline{Q}_{ij,\gamma}\right) t_k$$

$$(i = 1,2,6; j = 1,2,6) \qquad (3)$$

In formula 3, $N_\alpha, N_\beta, N_\gamma$ represent the ply numbers of α，β，γ degree；t_k is the thickness of single layer.

Through solving equation set, the optimized laminate will be equivalent to a symmetric balanced laminate with engineering available ply orientation. The thickness and stiffness properties of laminate stay the same after equivalence.

2.3.2 Surface Fitting

During the optimization, the thickness of each element is optimized independently, the thickness along or cross the chord are discontinuous. Each element is considered as a discrete point and the value of coordinate x and y of the center grid is taken as the value of x and y for this discrete point. The thickness of laminate is the z value of this point.

For the scatted data in three direction space, the usual fitting method is interpolation and approaching fitting. These methods are usually using a smooth surface to approaching or through a series of irregular sample point to form the surface and represent with picture.

Considering the widely application of Bicubic patch and the demand of overall fairness, this research adopts the Bicubic patch to realize the surface fitting of the optimized laminate.

Bicubic patch is showed in formula 5：

$$f(x, y) = (a_0 + a_1 x + a_2 x^2 + a_3 x^3) \cdot (b_0 + b_1 y + b_2 y^2 + b_3 y^3) \qquad (5)$$

3 Application

Based on the method and process introduced in chapter two. A optimization process is set up based on a composite wing model. The optimized design fulfills the weight minimized design, and the working strains are lower than the allowable strain under 30 load cases.

3.1 Model Description

A composite wing optimization design is completed with the process displayed in figure 2. The design elements are showed in figure 3. The skin is symmetric laminate and the total number of design elements is 298. The design variables are more than 10^5.

The thickness of the element starts from the minimum value and increases gradually with the process. The weight increment is constant every step and relative small. This could prevent the optimization's divergence and make sure that the optimized model has the minimum weight.

The optimization includes 30 load cases' analysis.

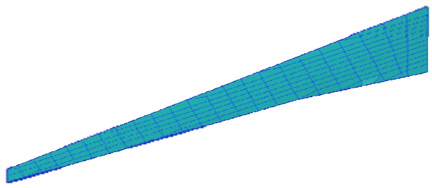

Fig. 3 The Design Element of a Composite Wing

3.2 Optimization Process

Firstly, the severity of the model under 30 load cases is analyzed and the result is displayed in Fig 4. The longitudinal axis stands for the number of load case and the transverse for the element numbers that fail to meet with the objective function under the corresponding load case. In each step of optimization, only one load case is taken into consideration. Therefore, after the optimization running for several steps, the current optimized result should be checked under other load cases. For those fulfill the allowable strains, the optimization will skip. For those fail, the optimization will continue under the corresponding load case.

From fig 4, it implies that the amount of failure elements is nearly the same in the first five load cases and much more than the other load case. Therefore, the load case one is selected as the basic load, not only because it is the most serious load but also for it could represent the most load case.

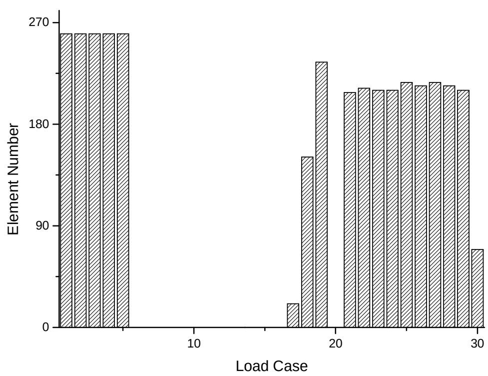

Fig. 4 The Analysis of Objective Value of Initial Model

The optimization is carried out with formula 1 and it is a minimum optimization. Altogether, there are three stages optimization.

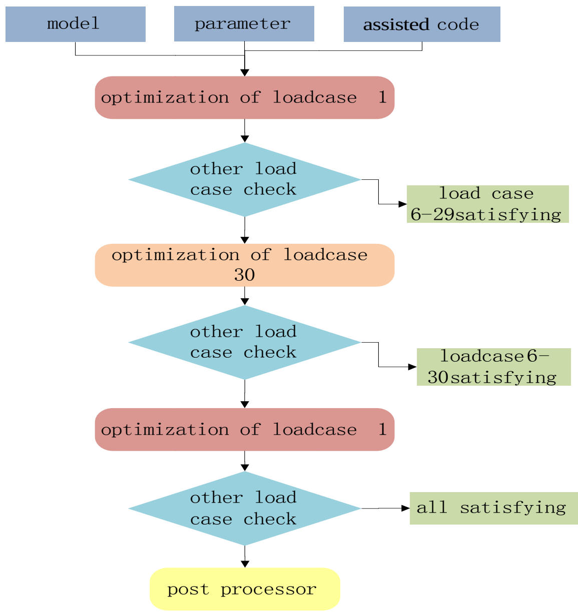

Fig. 5 The Load Case Selection in Optimization

The load case selection can be seen from Fig 5. The input include FEM model, parameter files and assisted code. This assisted code specially refers to those of assisting to obtain the objective value from the result file. For different objective function, the corresponding mode in the process fixed in the platform will be substituted with the assisted code. Based on SAMOS, it is easier for designer to programming the mode for specific model and demand according to the definition of input and output of the platform. Therefore, there is no need to organize a new process and greatly save the time and human resources.

3.3 Optimization Result

The first stage of optimization runs for 150 steps (only the first 75 steps are showed in figure 6). the objective value has decreased obviously.

Figure 7 reflects the sensitivity of outer loop. The lower the sensitivity becomes, the less impossibility for the improvement of optimization. After analyzing the result and sensitivity, the result of step 57 (the red asterisk in figure 6) is chosen as the beginning state of stage 2.

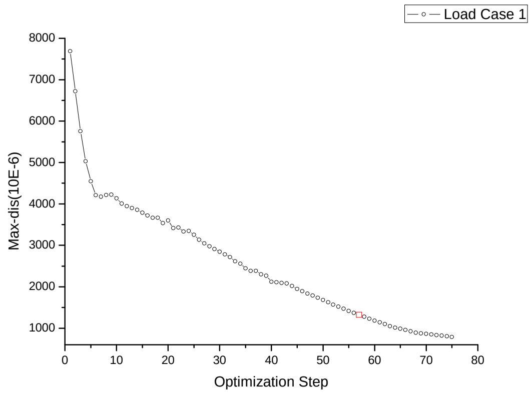

Fig. 6 Optimization Result of Load Case 1 in Stage One

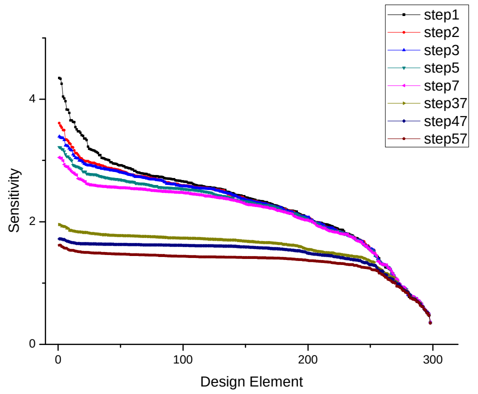

Fig. 7 The Sensitivity in Outer Loop

From the diagram of figure 8 to figure 10, it can be deduced that the tension and compression strain decrease greatly but are still higher than the allowable strain. For the shear strain, except of load case 30, the working strains are all lower than the allowable strain. If the optimization continues with load case 1, the item of shear in objective function equals to zero. For those elements that sustain high tension or compression, it will help to alleviate the strain. But for those under serious shear condition, the thickness of skin will not increase. The shear strain will still higher than the allowable strain under load case 30. Therefore, in stage 2, the optimization will be carried out with load case 30 in order to decrease the shear strain.

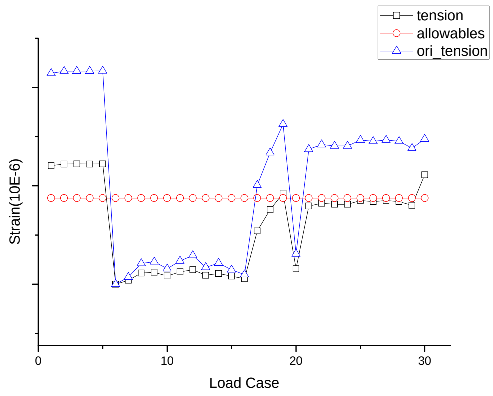

Fig. 8 Comparison of Tension in Stage One

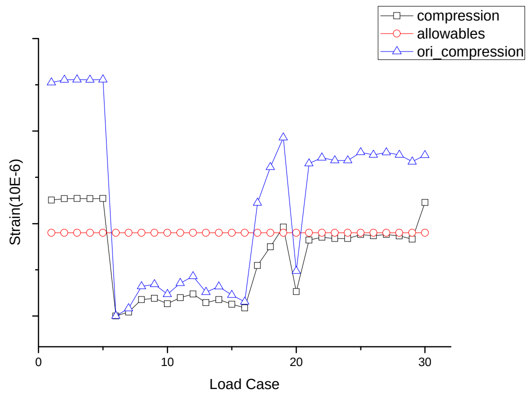

Fig. 9 Comparison of Compression in Stage One

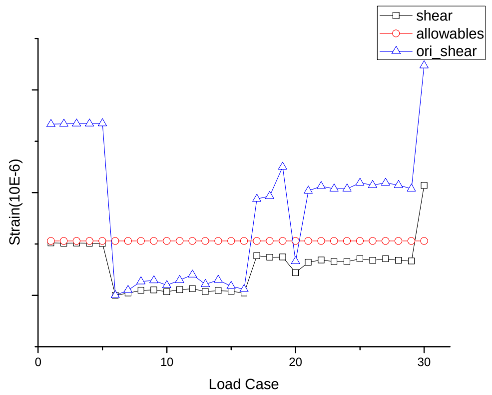

Fig. 10 Comparison of Shear in Stage One

The objective value of stage 2 can be seen from figure 11. It shows that after 16 steps' optimization, the objective value becomes stable and equals to zero. Through the definition of objective function, it can be deduced that all the working strains are lower than the allowable strains under load case 30.After analyzing the working strain under all the load case, it shows that the shear strain fulfill the allowable strain under all the load case. Except for the load case 1 to 5 and 30, the tension and compression strain also lower than the allowable strain. According to the conclusion from stage one, optimization with load case one based on the current result will decrease the tension and compression strain.

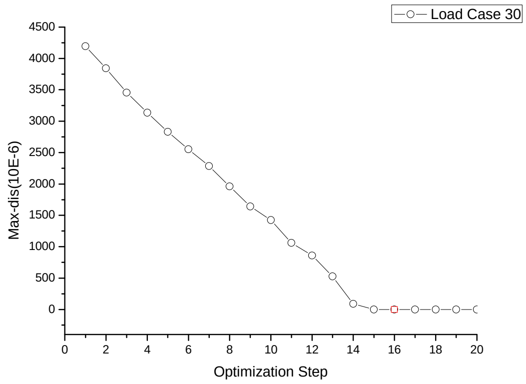

Fig.11 Optimization Result in Stage Two

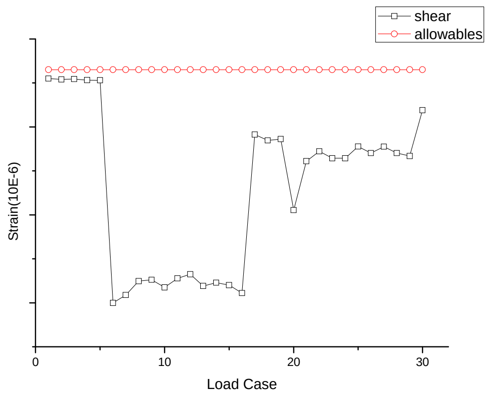

Fig.12 Comparison of Shear in Stage Two

The result of step 16 in stage 2 is chosen as the start state for the following optimization. There are 50 steps in stage 3 and the comparing of strain between working strain and allowable strain show that strains in three directions meet the demand of design.

After the optimization, the post processing is carried out. The result of equivalent design is not presented here. Figure 13 shows the distribution of thickness along the chord of upper skin. Obviously, through the surface fitting, the distribution of thickness become more reliable and manufacture available. The result from the post processing also needs to be checked under all the load cases and the analysis proves that the strength property hardly changes after the post processing.

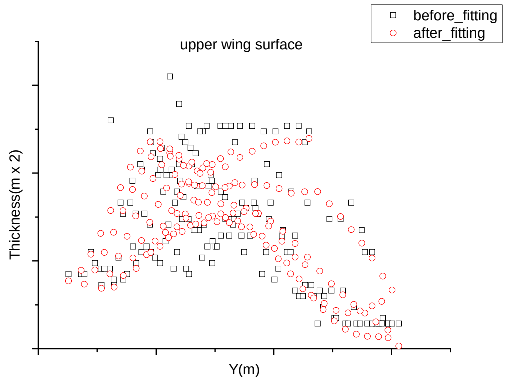

Fig. 13 Distribution of Thickness of Upper Skin

4 Conclusions

Through the composite wing design, it is proved that the method and process stated in chapter 2 is efficient. The optimization design makes the working strain of skin element become lower than the allowable strain with the minimum increment on weight.

It also implies that the cut-off step in each load case when using formula two as objective function will also influence the result. Both the objective value curve and the sensitivity curve are needed to choose the cut-off step.

The post processing will make the optimized result easier to manufacture. After the post processing, the strength property will be getting better sometimes because of the thickness added for rounding.

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Contact Author Email Address

zrbuaa@sina.com

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