OPTIMIZATION OF AIRCRAFT WING STRUCTURE

Adil A. AL-Moosawy **Qasim H. Bader** **Ahmed R. Madeh**

adil_almoosway@yahoo.com drqasimbader@yahoo.com Ahmedraee@yahoo.com

College of Engineering-University of Babylon

ABSTRACT

In this research, the optimum design of a manned aircraft wing structure at speed (M=0.4) is estimated for both isotropic and orthotropic material. Firstly the stress analysis for wing structure due to aerodynamic loads is computed. The wing is considered as a cantilever through the contact points with the aircraft fuselage. The stress distribution and deflection for each point of the wing structure is found for both isotropic and orthotropic material. Secondly, the optimum design (minimum weight) for both isotropic and orthotropic material is estimated. Two methods were used to find the optimum design of the wing structure. In the first method the MORPHING criteria was programmed and used as optimizer program in conjunction with ANSYS[11] program as solver program, Ansys Parametric Design Language (APDL) is used to write the MORPHING method. In the second method, the ANSYS[11] program is used for both analysis and optimization. The results found by using the first method show (22.7%) weight reduction for isotropic material and (23.2%) for orthotropic material. The result found from second method show (24.4%) weight reduction for isotropic material and (24.1%) weight reduction when using orthotropic material.

Keywords: optimum design, shell structure, optimization criteria.

تحقيق الأمثلية لتركيب جناح طائرة

عادل عباس الموسوي قاسم حسن بدر أحمد راعي مديح

الخلاصة

في هذة البحث تم أيجاد التصميم الامثل لجناح طائرة مسيرة ثابت عند سرعة (M=0.4).
يشمل التصميم كلا من قشرة الجناح والتراكيب المقوية له (stiffeners) مثل (ribs and spars)
ولنوعين من المواد (المتجانسه والغير متجانسة) , أولا تم انجاز تحليل متكامل للأجهادات المتكونة على
جميع أجزاء الجناح نتيجة الاحمال الأيروديناميكية حيث تم التعامل مع الجناح كونه عتبة مثبتة
(cantilever) عند نقطة الأتصال ببدن الطائرة. عملية تحليل الأجهاد أنجزت على كلا النوعين من

المواد الداخلة في تصميم الجناح وهي المواد المتجانسة (isotropic materials) والمواد الغير متجانسة (composite materials). ثانيا تم إيجاد أفضل تصميم(أقل وزن) ولكلا النوعين من المواد المتجانسة والغير متجانسة. التصميم الأمثل للجناح تم أيجاده بطريقتين , الأولى بأستخدام طريقة (Morphing) التي تم برمجتها بأستخدام لغة (APDL) المتوافقة ببرنامج (ANSYS11) والتي من خلال هذه اللغة يمكن أستخدام برنامج (ANSYS11) لتحليل النتائج فقط أما التصميم الأمثل فيكون بالطريقة الجديدة.أما في الطريقة الثانية فتم بأستخدام برنامج (ANSYS11) للتحليل وإيجاد أفضل تصميم. النتائج المحصلة لأفضل تصميم (أقل وزن) لهذا الجناح بأستخدام الطريقة الأولى (Morphing) كان التخفيض (22.7%) للمواد المتجانسة و (23.2%) للمواد الغير متجانسة أما النتائج المحصلة من استخدام الطريقة الثانية تمكنا من الحصول على تخفيض (24.4%) للمواد المتجانسة و (24.1%) للمواد الغير متجانسة.

NOMENCLATURE

Unit	Definition	Symbol
σ_i	Normal stress in i-direction	N/m^2
ε_i	Normal strain in i-direction	---
ξ	Tsai-Wu failure index	---
$\sigma^f_{t_i}$	Failure stress in layer i-direction in tension	N/m^2
$\sigma^f_{c_i}$	Failure stress in layer i-direction in compression	N/m^2
$\sigma^f_{c_{ij}}$	Failure shear stress in layer *ij*-plane	N/m^2
x_i	Design variable	m, deg.
g_i, h_i, w_i	State variable	m,N/m^2
$f(x)$	Objective function	m^3
N	Number of design variable	---
N	Number of design sets	---

1. INTRODUCTION

The optimum structural design of aircraft wing is an important factor in the performance of the airplanes i.e. obtaining a wing with a high stiffness/weight ratio and sustaining the unexpected loading such as gust and maneuvering situations. Optimization process has been written using ANSYS11 Parametric Design Language (APDL) in first method, in order to be used in conjunction with the ANSYS11 package capability, where the ANSYS11 was used to analyze the stress in structure and to easily transfer the information between the optimization and the analysis program. In second method, optimization process was performed using ANSYS11 program (sub-problem approximation method).

Erdogan Tolga Insuyu, 2010, aimed to increase the aerodynamic efficiency of the aerial vehicles is examined. Among different alternatives, the methodology of increasing the aerodynamic efficiency is chosen as change in camber. The background of the study is established by performing 2D CFD analyses on differently cambered airfoils generated from the selected NACA4412 airfoil via ANSYS®/FLUENT software.

Sakarya,Evren, 2010 presents a camber morphing concept as an alternative to existing plain flap aileron type hinged control surface used in wings. Structural aspect of the concept is investigated with static nonlinear finite element analysis by using MSC NASTRAN .In order to assess the aerodynamic characteristics; CFD based 2D solution is obtain using ANSYS Fluent package.

Vinson, 1986, presented closed-form analytical solution for the analysis and design of minimum weight, composite material hex-cell and square cell honey comb core sandwich and panels subjected to in-plane uniaxial compressive loads. These methods account for overstressing, overall buckling, core shear instability, face wrinkling, and mono cell buckling. The methods insure minimum weight, as well as provide methods to compare various material systems, compare honey comb sandwich construction with other panel architectures.

Iyengar and Joshi 1986, found the minimum weight design of a laminated fiber-rein forced composite plate subjected to in plane and transverse loading. Restrictions are imposed on the buckling load and transverse deflection. The fiber orientation and thickness of each ply are treated as design variable.

Canfield, Grandhi and Venkayya, 1988, determined what techniques are reliable and efficient for optimization of a complex design problem. The study examined the relative numerical performance of various optimization methods as candidates for a hybrid algorithm using optimality criteria and mathematical programming methods, several optimization programs were used to design truss-and wing type structures.

Rohl, Marris and Schrage 1995, presented a combined procedure for the aerodynamic and structural optimization of a high-speed civil transport wing. Primary goal of the procedure is the determination of the jig shape of the wing necessary so that it deforms into its optimum shape in cursive flight. The wing structure is sized subject to strength, buckling, and aero elastic constraints. Various analyses have been performed with different material configurations and structural-concepts.

Liu 2001, used a two level optimization procedure for wing design subject to strength and buckling constraints. The design variables are the orientation of ply and the number of plies of each orientation. The genetic algorithms and response surface method were used to continue the optimization.

The objective of this paper is to develop accurate model for such optimal design studies through design the structure of wing that combine the composite and isotropic materials in order to obtain high strength/weight ratio for finding optimum design.

2. DESIGN OPTIMIZATION

2.1. Morphing method

The main steps required to define the morphing method was shown in figure (1) are given by **Kasim** 2003, as follows:

1. Set up a dense finite element mesh for the maximum expected design domain of the structure.

2. Apply the kinematics boundary conditions, loads, material properties, etc.

3. Specify the criteria to be used to optimize the structure, for example the Von Misses stress.

4. Specify the Morphing driving parameters, for example the maximum Von Misses stress of the structure domain.

5. Define a set of allowable discrete volumes in decreasing order of the strength that each original element of the structure is made. The discrete set could be a set of plate thickness, modulus of elasticity or density or other.

This set could be written in the following:

$$X_s = \{A_1, A_2, A_3, \dots A_N\} \quad (1)$$

Where A is the beam cross sectional area with $A_1 > A_2 > A_3 > \cdots > A_{N.}$

6. Carryout a linear static finite elements analysis of structure.

7. Using the Morphing inequality equation, determine if there are the structure that satisfy the following:

$$\sigma_{structure} \leq \sigma_{VM_{max}} \quad (2)$$

If an element satisfies this equation, the elements discrete value which is allowed to the next discrete value in the next. Since the set is arranged in decreasing order of strength, this new value will be weaker than the one it replaces.

8. If a state is reached where no element of the structure satisfies equation (5.2), a steady state and local optimum has been reached. The steady state number is then incremented by 1, and steps (7) and (8) are repeated.

9. Step (6) through (9) is repeated until the desired minimum volume or weight of the structure has been reached.

2.2. Sub-problem approximation method

This method of optimization can be described as an advanced, zero-order method in that it requires only the values of the independent variables (objective function and state variable) and not their derivatives. The dependent variable is first replaced with approximation by means of least squares fitting, and the constrained minimization problem is converted to an unconstrained problem using penalty functions. Minimization is then performed every iteration on the approximated, penalized function (called the sub-problem) until convergence is achieve or termination is indicated. For this method each iteration is equivalent to one complete analysis loop which was detailed by **Ajaykuma**r **Menon** 2005.

While working towards an optimum design, the ANSYS optimization routines employ three types of variables that characterize the design process: design variables, state variables, and the objective function. These variables are represented by scalar parameters in ANSYS program. The independent variables in an optimization analysis are the design variables. The vector of design variables is indicated by:

$$x = \lfloor x_1 \; x_2 \;\; x_3 \ldots x_n \rfloor \qquad (3)$$

Design variables are subject to *n* constraints with upper and lower limits, that is:

$$\underline{x}_i \leq x_i \leq \overline{x}_i \qquad (i = 1, 2, 3 \ldots, n) \qquad (4)$$

Where:

n is the number of design set.

The design variable constraints are often referred to as side constraints and define what is commonly called feasible design space.

Minimize

$$f = f(x) \qquad (5)$$

Subjected to

$$g_i(x) \leq \overline{g}_i \qquad (i = 1, 2, 3 \ldots, m_1) \qquad (6)$$

$$\underline{h}_i \leq h_i(x) \qquad (i = 1, 2, 3 \ldots, m_2) \qquad (7)$$

$$\underline{w}_i \leq w_i(x) \leq \overline{w}_i \qquad (i = 1, 2, 3 \ldots, m_3) \qquad (8)$$

Where:

f is the objective function

g_i, h_i, w_i are the state variables containing the design, with underbars and over bars representing lower and upper bounds respectively .

$m_1 + m_2 + m_3$ are the number of state variables constraints with various upper and lower limit values.

The state variables can also be referred to as dependent variables in that they vary with the vector x of design variables. Equation (5) to (8) represent a constrained minimization whose aim is the minimization of the objective function f under the constraints imposed by equations (4), (6), (7), and (8).

3. FAILURE CRITERIA FOR ORTHOTROPIC MATERIAL

To evaluate if either type of failure has occurred in the structure, a failure criterion must be selected from those available. The three most common ones are Maximum Stress theory, Maximum Strain theory and Tsai-Wu Tensor theory which is energy criterion. When want to look at a general but conservative failure estimate, the Tsai-Wu failure criterion will be used to determine the safety factor of the structure. The main advantage of this theory due to discusses the interaction between normal stresses and shear stresses .Detailed of the final equation of this theory as follow (Burnside [10]):

$$\xi = A + B \tag{9}$$

Where:

ξ = Failure index.

$$A = -\frac{\sigma_x^2}{\sigma_{x_t}^f \sigma_{x_c}^f} - \frac{\sigma_y^2}{\sigma_{y_t}^f \sigma_{y_c}^f} - \frac{\sigma_z^2}{\sigma_{z_t}^f \sigma_{z_c}^f} + \frac{\sigma_{xy}^2}{\left(\sigma_{xy}^f\right)^2} + \frac{\sigma_{yz}^2}{\left(\sigma_{yz}^f\right)^2} + \frac{\sigma_{xz}^2}{\left(\sigma_{xz}^f\right)^2} + \frac{C_{xy}\,\sigma_x \sigma_y}{\sqrt{\sigma_{x_t}^f \sigma_{x_c}^f \sigma_{y_t}^f \sigma_{y_c}^f}} + \frac{C_{yz}\,\sigma_y \sigma_z}{\sqrt{\sigma_{y_t}^f \sigma_{y_c}^f \sigma_{z_t}^f \sigma_{z_c}^f}} + \frac{C_{xz}\,\sigma_x \sigma_z}{\sqrt{\sigma_{x_t}^f \sigma_{x_c}^f \sigma_{z_t}^f \sigma_{z_c}^f}} \tag{9a}$$

$$B = \left(\frac{1}{\sigma_{x_t}^f} + \frac{1}{\sigma_{x_c}^f}\right)\sigma_x + \left(\frac{1}{\sigma_{y_t}^f} + \frac{1}{\sigma_{y_c}^f}\right)\sigma_y + \left(\frac{1}{\sigma_{z_t}^f} + \frac{1}{\sigma_{z_c}^f}\right)\sigma_z \tag{9b}$$

4. RESULTS AND DISCUSSIONS

Structural analysis was achieved by using the $ANSYS$[11] package in order to obtain the element stresses distribution on the wing structure and the internal structure which included the ribs and spars along element coordinates axis, the linear and angular displacements of the nodes $(u, v, w, \theta_{xi}, \theta_{yi}, \theta_{zi})$ along global coordinate axis by using isotropic material and the element criteria Tsai-Wu failure index (ξ) which is used for orthotropic materials and represents the inverse of safety factor.

Figure (2) and (3) shows Von Misses stress distribution on the wing box and the internal structure of the wing box which includes the main spar (front spar), secondary spar (rear spar) and ribs. Its note that the maximum Von Misses stress occur at the distance of 0-15% from the wing constraint or fixed edge at the root [$\sigma_{max} = 50.5$ MPa] due to bending moment is maximum at this location. The stresses are also high at the corners at which spar webs extending from the wing and root rib intersects. The geometrical discontinuity is the reason for high stresses at these locations. It is notice Von Misses stress decreasing along the length of wing in the direction of the tip in which bending moment becomes minimum.

Figure (4) represents vertical displacement field of the wing box (uy). From figure the maximum deflection occurs at the free side of the wing or at the tip [$(uy)_{max}$=1.25 cm], and the deflection is the inversely proportional with the stiffness values.

5. OPTIMIZATION OF WING STRUCTURE

5.1. Optimization of wing structure using isotropic material of shell structure.

Figures (5), (6) and (7) show rib, spar and skin thickness respectively (design variable) versus set number. From these figures the optimum rib thickness value (0. 504 mm), optimum spar thickness value (0. 506 mm) and optimum skin thickness value (0. 994 mm). Divergence occurs at start of the iteration and the thickness values at these set numbers do not represent the optimum values. After this set number the convergent occurs at set number (8) after which the thickness value remains constant which represents the correct result of thickness value. All optimum thickness of rib, spar, skin occurs at set number (16) and due to this set number the volume becomes minimum for required constraint (state variable).

Figure (8) shows the vertical displacement (state variable) versus set number. From this figure the optimum vertical displacement value (0.0145 m) at set number (16). Divergent occurs at start the iteration and the displacement value at these set numbers does not represent the optimum value. After this set number the convergent occurs at set number (9) after which the displacement value remains constant which represents the correct result of vertical displacement value.

Figure (9) shows Von Misses stress (state variable) versus set number. From this figure the optimum Von Misses stress value (101 Mpa) at set number (16). Divergence occurs at start the iteration and Von Misses stress value at these set numbers does not represent the optimum values. After this set number the convergence occurs at set number (12) after which Von Misses stress value approximately remains constant which represents the correct result of Von Misses stress value.

Figure (10) show total volume (objective function) of the wing box versus set number. From this figure the optimum volume (0.0017 m3) at set number (16), and this value represents 77.3 % from the analysis value. Divergence occurs at start of the iteration and the total volume value at these set numbers does not represent the optimum values. After this set number, the convergence occurs at set number (9) after which the total volume value remains constant which represents the correct result of the total volume value. Total volume represents as a function for thickness of ribs, spars and skin (design variables).

6. CONCLUSIONS

The major and general observations and conclusions for this work can be listed below:

1. From the structural results it is noticed that the maximum Von Misses stress occur at the distance of 0-15% from the wing constraint or fixed edge at the root due to bending moment is maximum at this location.

2. The stresses are also high at the corners at which spar webs extending from the wing and root rib intersects. The geometrical discontinuity is the reason for high stresses at these locations.

4. The optimum design (minimum weight) of wing structure by using morphing method shows a reliable method and gets best result when comparing with the result obtain from using ANSYS program.

5. The optimum design of multi layer fiber-reinforced laminated shell structure of the wing by new method (morphing) predicted by this dissertation can be obtain absolutely based on lowest failure index (Tsai-Wu) that not neglect the inter-lamination effect.

6. Compared with other works, the presented work includes load calculation, stress analysis and optimum design using two approaches offers signification simplicity and set a good result for both types of materials.

7. Finally, the weight reduction to real wing structure shows the ability to get bester new design of the wing.

5.2. Optimization result for orthotropic material

Figure (11) shows Tsai-Wu failure index (objective function) versus set number. From figure the analysis value of Tsai-Wu failure index (1.61) was decreased until it reached the optimum value (0.1788) at set number (15). At this set number, convergence was occurred and Tsai-Wu failure index becomes minimum and at this set number fibers orientation angles (32°/−51°/−19°/4°) represent optimum angles for all layers as in figure (13).

Figure (12) shows vertical displacement (uy) versus set number. From figure, the analysis value of displacement (12.546 mm) starts decreasing with set number until it reaches the optimum value (11.4 mm) at set number (15) in which Tsai-Wu failure index becomes minimum. Divergence occurs at start the iteration and the vertical displacement value at these set numbers does not represent the optimum values. After this set number convergence occurs at set number (8) after approximately remains constant.

Now the best angle each layer of the skin was chosen and the structure ready to second stage of optimization to get the best structural volume.

Figures (14) to (19) show first, second, third, fourth layers, ribs and spars thickness (design variable) respectively versus set number. From figure the analysis values of thickness start to decrease with set number which represents the divergence process until it reaches the optimum value at set number (20) in which Tsai-Wu failure index for all layers (state variable) become less than one (0.96) and the total mass become minimum (3.438 kg). Divergence occurs at the start of the iteration and the thickness value at these set numbers does not represent the optimum values. After this set number the convergence occurs at set number (7) after which the thickness value remains constant which represents the correct result of the thickness value.

Figures (21) to (23) show mass (objective function) of internal structure (ribs and spars), skins and wing box respectively versus set number. From figures the analysis values starts in decrease which represents the divergence process until reach the optimum values in which minimum mass and Tsai-Wu failure index for all layers less than one (0.96). The convergence occurs at set number (9) for mass of internal structures (ribs and spars), set number (9) for mass of the skin and at set number (9) for mass of the wing box after which the mass value remains constant which represents the correct result of the mass value which was selected at set number (20). All discussed figures will be represented in table (2).

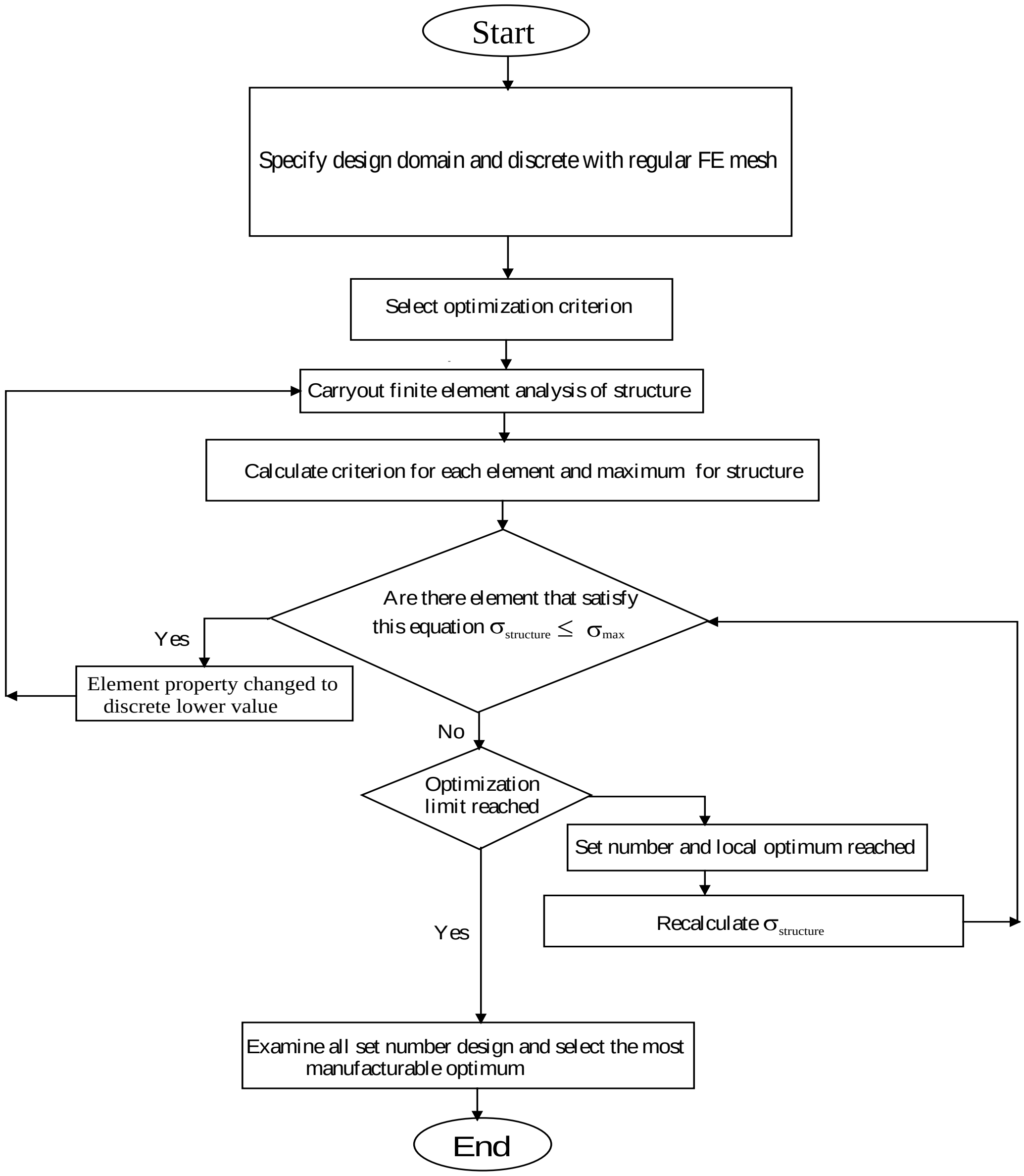


Fig.1 flow chart of the logical steps of the morphing method

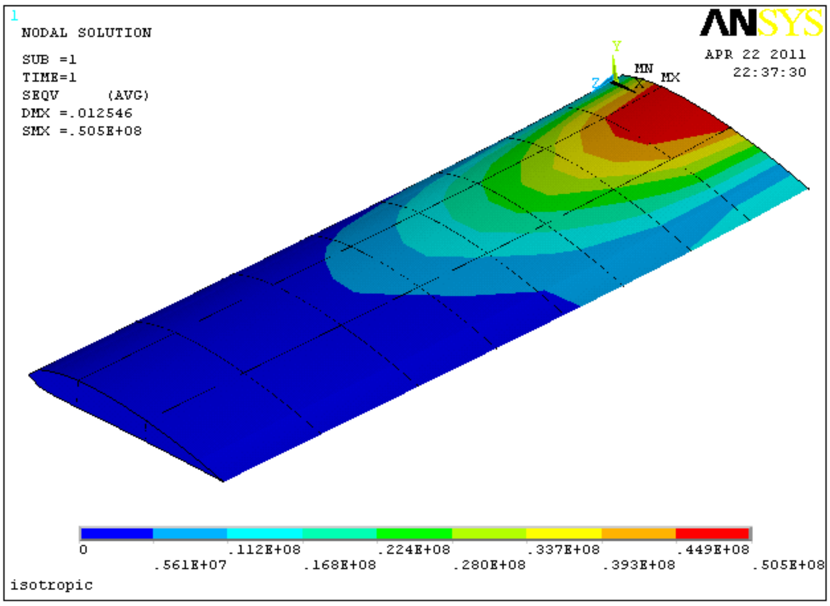


Fig.2 Von Misses stress distribution on the wing box.

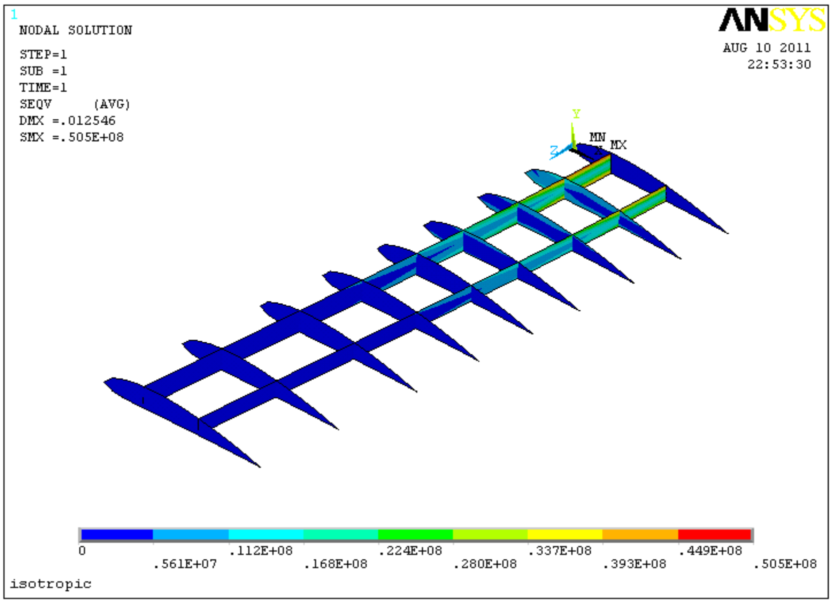


Fig.3 Von Misses stress distribution on internal structures of the wing box.

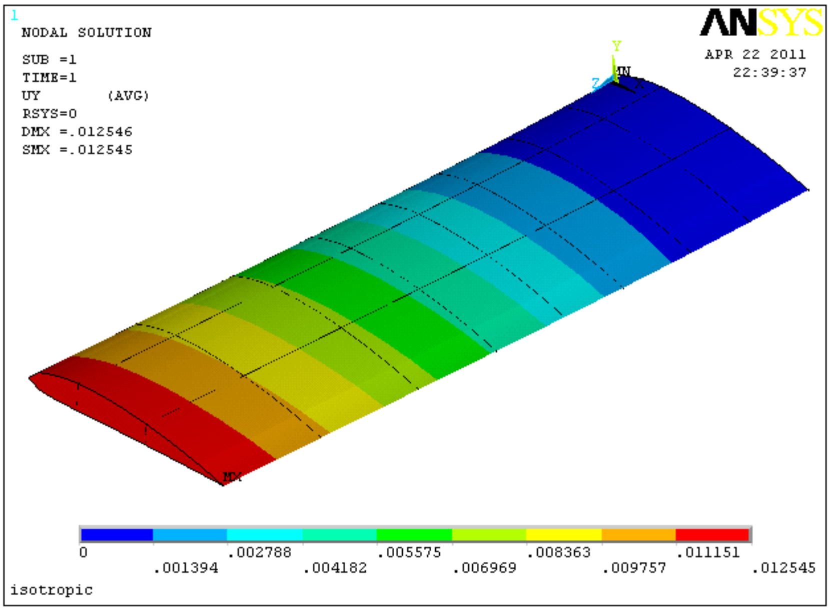


Fig.4 vertical displacement field-uy-on the wing box.

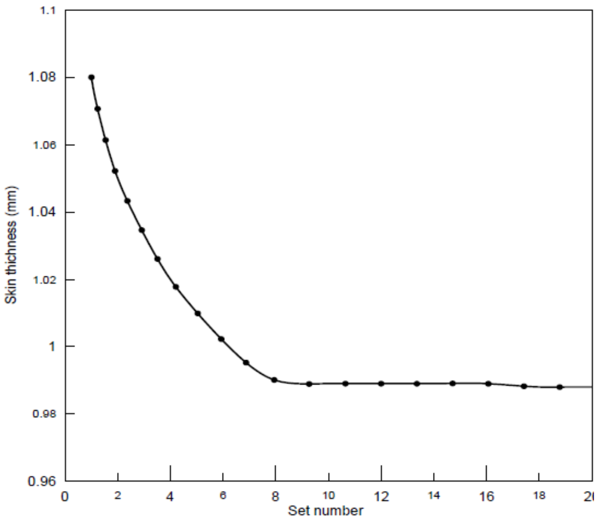


Fig.5 ribs thickness versus set number

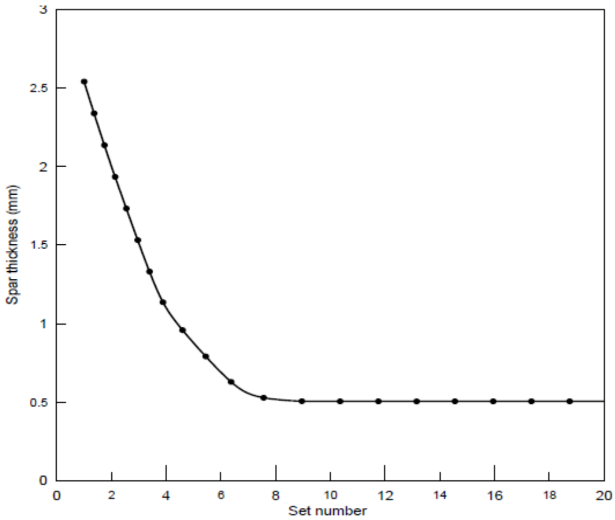
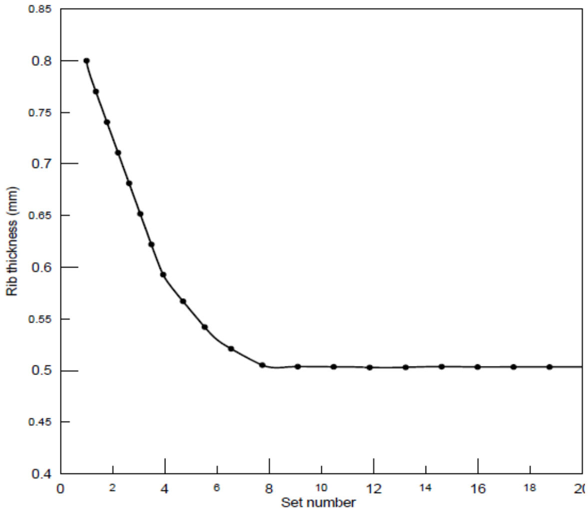


Fig.6 spars thickness versus set number



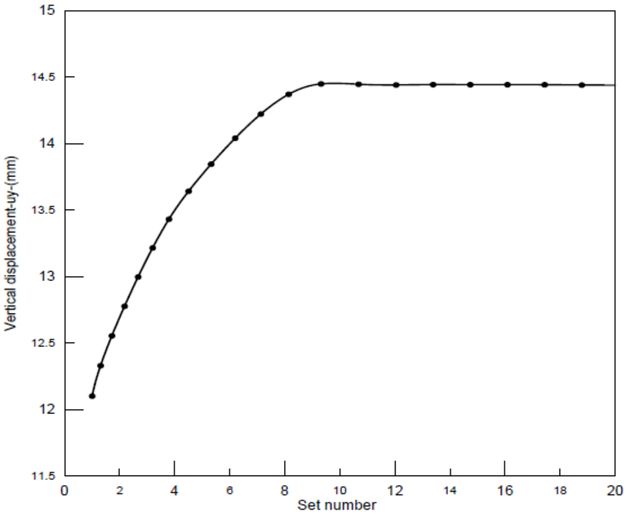
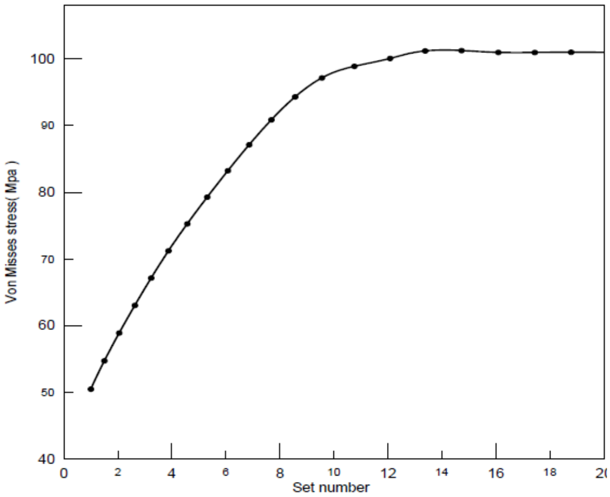


Fig.7 skin thickness versus set number.

Fig.8 vertical displacement (uy) versus set number.



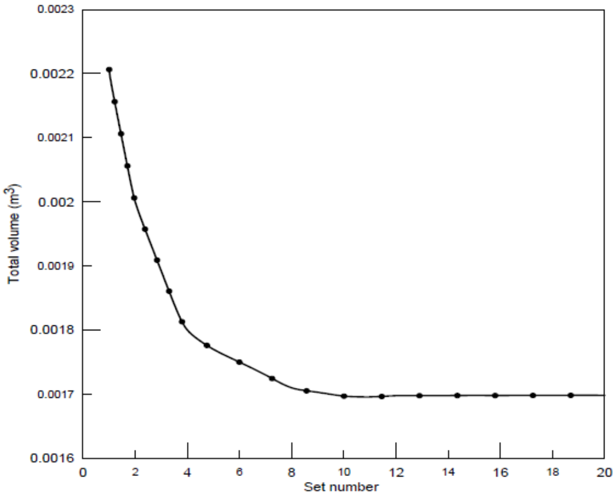


Fig.9 Von Misses stress versus set number.

Fig.10 Total volume of the wing box versus set number.

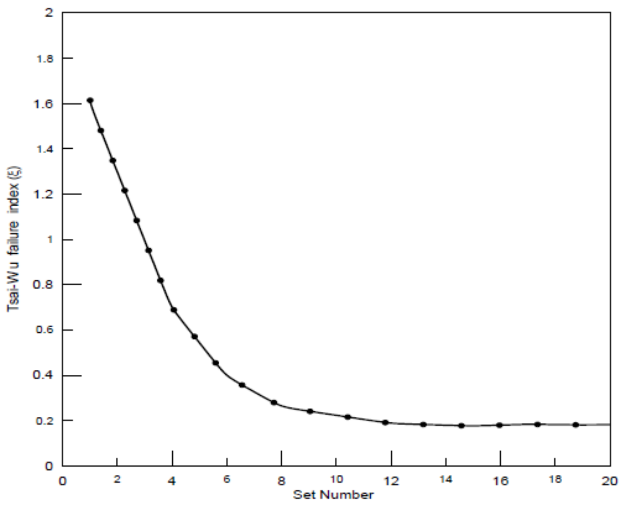


Fig.11Tsai-Wu failure index versus set number

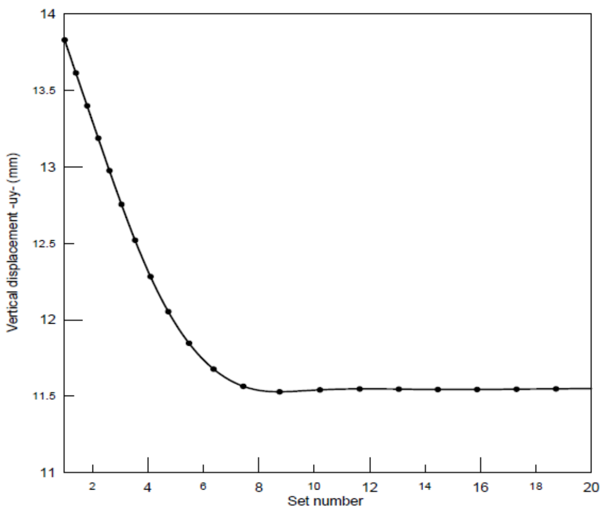


Fig.12 vertical displacement versus set number.

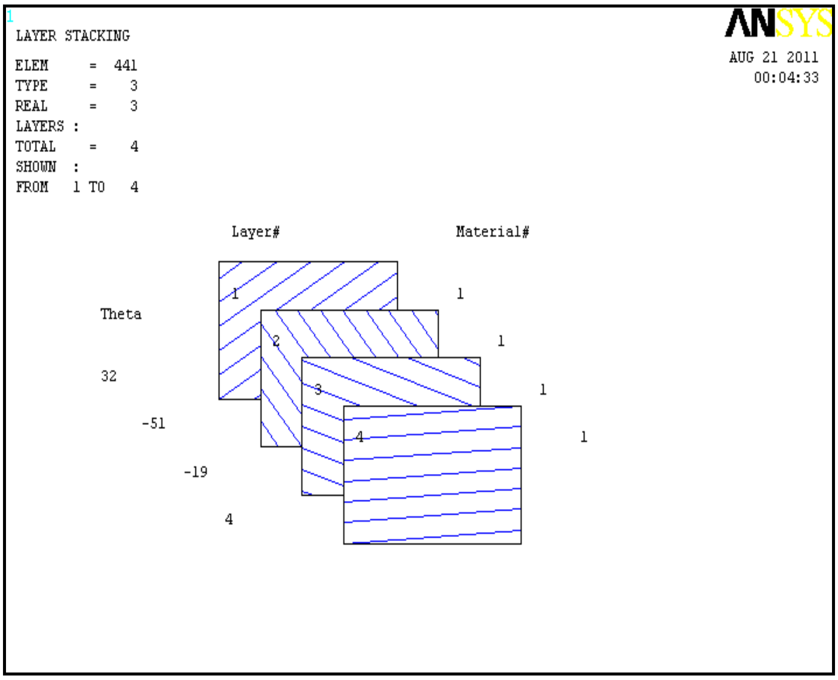


Fig.13 Optimum layers angles.

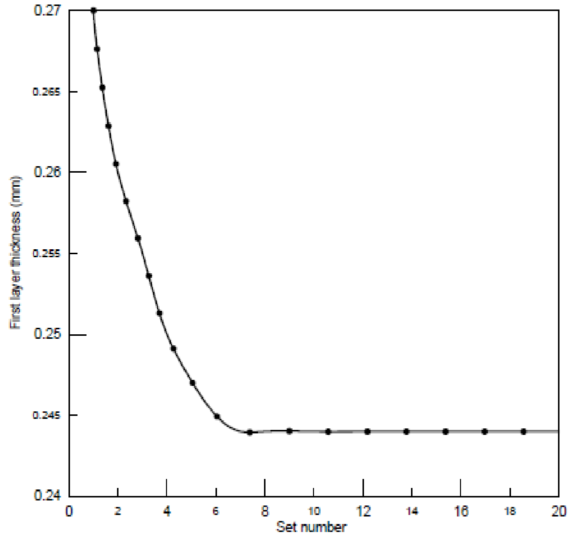


Fig.14 first layer thickness versus set number.

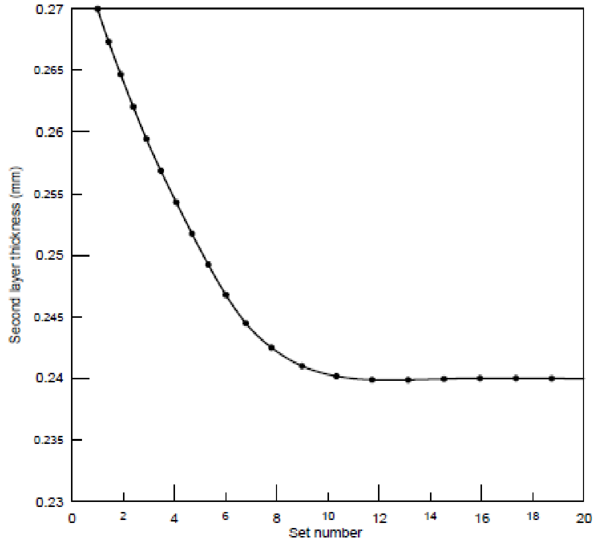


Fig.15 second layer thickness versus set number.

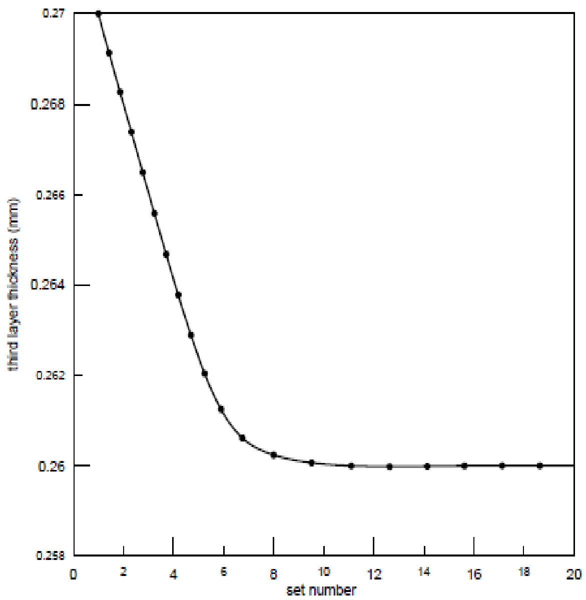


Fig.16 third layer thickness versus set number.

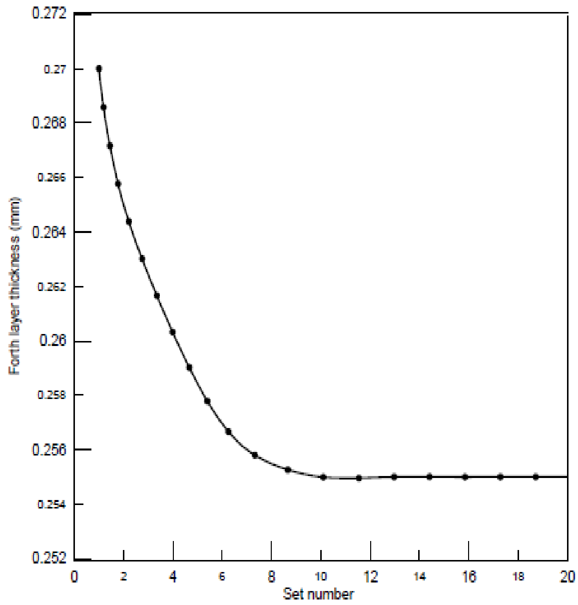


Fig.17 fourth layer thickness versus set number.

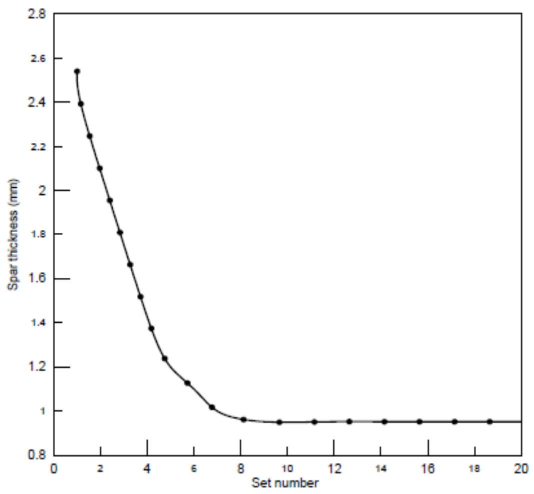


Fig.18 rib thickness versus set number.

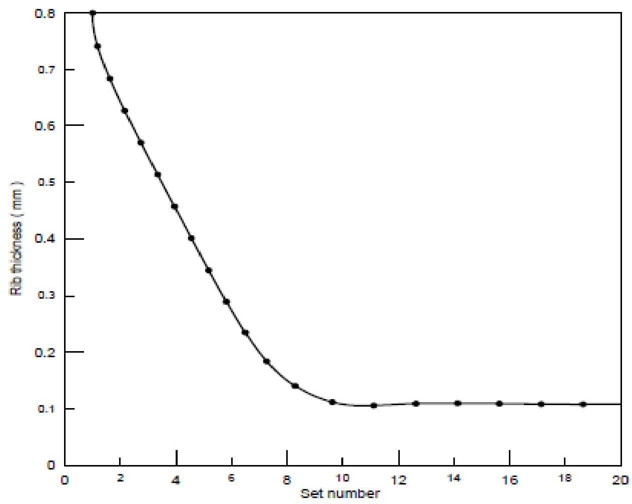


Fig.19 spar thickness versus set number.

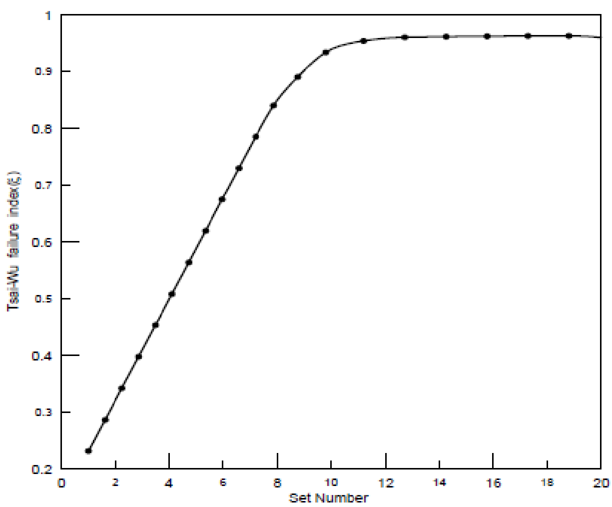


Fig.20 Tsai-Wu failure index versus set number.

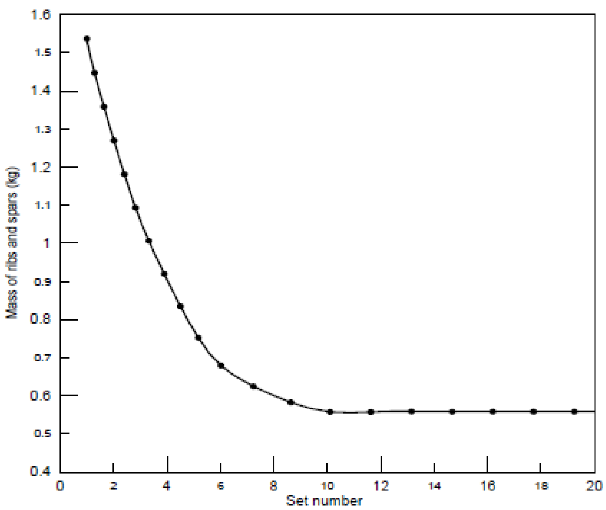


Fig.21 mass of ribs and spars versus set number.

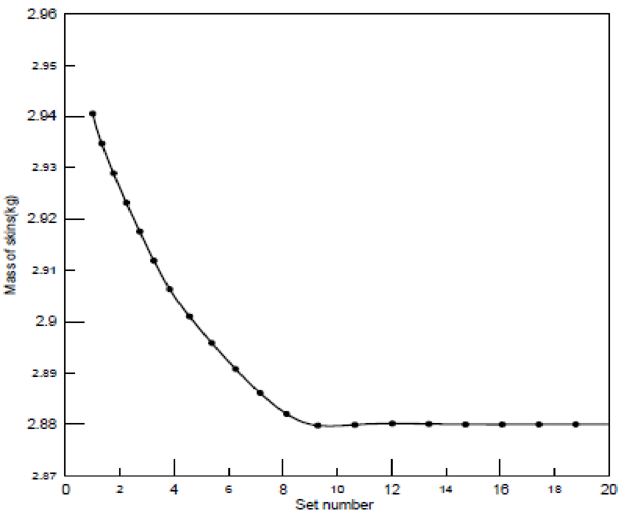


Fig.22 mass of skins versus set number.

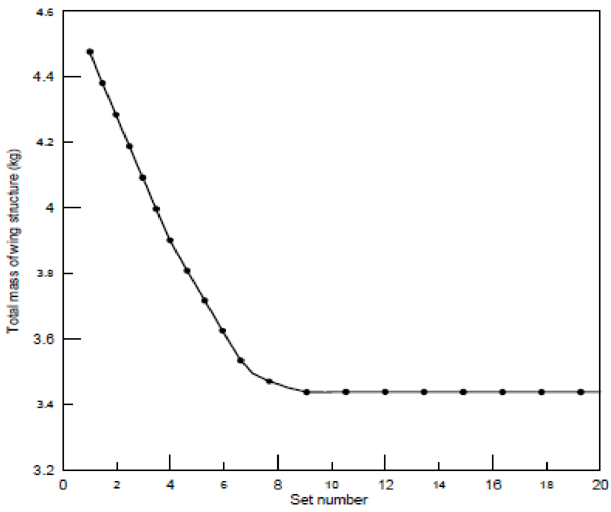


Fig.23 total mass of wing box versus set number.

Table 1 Result of optimization analysis.

Description	Analysis Value	Optimum value	
		APDL method	ANSYS (sub-problem method)
t_{rib} (DV)	(0. 8 mm)	(0. 504 mm)	(0.5 mm)
t_{spar} (DV)	(2.54 mm)	(0. 506 mm)	(0.501 mm)
t_{skin} (DV)	(1.08 mm)	(0. 994 mm)	(0.98 mm)
u_y (SV)	(12.546 mm)	(14.5 mm)	(14.8 mm)
σ_{von} (SV)	(50.5 Mpa)	(101 Mpa)	(105 Mpa)
Total volume (obj)	(0.0022 m^3)	(0.0017 m^3)	(0.00166 m^3)

Table 2 Optimum design parameters

Description	Layer number	Analysis Value	Optimum value	
			APDL	ANSYS (sub-problem method)
Layers thickness (DV)	layer 1	(0.27 mm)	(0.244 mm)	(0.24 mm)
	layer 2	(0.27 mm)	(0.24 mm)	(0.241 mm)
	layer 3	(0.27 mm)	(0.26 mm)	(0.24 mm)
	layer 4	(0.27 mm)	(0.255 mm)	(0.247 mm)
Rib thickness (DV)	_	(0.8 mm)	(0.1078 mm)	(0.11 mm)
Spar thickness (DV)	_	(2.54 mm)	(0.952 mm)	(0.9 mm)
Tsai-Wu failure index(ξ) (SV)	_	(0.1788)	(0.965)	(0.98)
Mass of ribs and spars (OBJ)	_	(1.537 kg)	(0.558 kg)	(0.548 kg)
Mass of skins (OBJ)	_	(2.94 kg)	(2.88 kg)	(2.85 kg)
Total mass of wing (OBJ)	_	(4.477 kg)	(3.438 kg)	(3.398 kg)

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