ENGINEERING OPTIMIZATION OF AERONAUTICAL STRUCTURES

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Abstract

Optimization techniques are being widely used and play a very important role in aeronautical structure design. With the growing application of advanced composite materials in industry, the structural analysis and design tailoring/optimization of composite structure has been an important topic in engineering research. Based on the experience gained for metal structure under the sponsorship of CAE a program system COMPASS has been developed for the analysis and design optimization of composite structures to explore the potential benefits of composite materials to improve the structural performance especially the aeroelasticity characters of the aircraft. The configuration of COMPASS and the technique used in COMPASS for structural tailoring design optimization under aeroelastic and strength onstraints on the lamina level are introduced briefly in this paper, including the structural/sensitivity analysis by substructuring methods, approximate numerical model for each optimization stage and series of approximation concepts. some sample problems including a simplified composite wing design under static aeroelasticity, flutter speed and other constraints for minimum weight are given to verify the general applicability of this system for development study and engineering applications.

I. Introduction

The high specific stiffness and strength and the designability of advanced composite material make it an attractive structural material for next generation of aircraft. About 25% weight saving could be attained by the use of this material. Further more, utilizing the directivity of material and coupling effects between deformation, benificial elastic deformation of wing under load could be attained by the weel known aeroelasticity tailoring technique[1,2] to improve the aricraft performance and its static and dynamic aeroelasticity characters. In fact, the aeroelasticity tailoring is a specific type of design optimization of structure to meet the strength and manufacturing requirments, and at same time to improve aerodynamic/control character, divergence and flutter speed and hence to improve the overall performance of the aircraft. A program system COMPASS (COMPosite structure Analysis and Synthesis System) has being developed, under the sponsorship of the Chinese Aeronautics and Astroautics Establishment, to provide a practical way to predict performance of composite structure and to optimize the structural design with aerodynamic, strength and aeroelasticity behaviours as object/constraints on the lamina-level basis. A basic version of COMPASS has been released to put into operation and has being successfully verified. The configuration of COMPASS and the technique used in COMPASS for structural tailoring/design optimization under aeroelastic and strength constraints are introduced briefly in this paper including structural/sensitivity analysis by substructuring methods, approximate numerical model for optimization in each design stage and series of approximation concepts. Some sample problems including a simplified composite wing design under static aeroelasticity, flutter speed and other constraints for minimum weight are given to verify the general applicability of this system for development study and engineering applications.

2. Configuration of COMPASS

The COMPASS is designed as a self-contained system with least dependance on other service/engineering programs, to implement structural tailoring at present and to realize multiple discipline design optimization including aerodynamics, structure and control etc in the furture. the main constituent parts are shown in Figure 1. The modular program structure is used with an executive/data file manipulate system at the kernel to control/support different functional modules such as structural statics and dynamics, aerodynamics/airload, aeroelasticity/ control respones, constraint screening, sensitivity analysis, opti8mization modeling and optimizer. The interfaces with user and external systems are well designed. A menu-drived program user interface is developed so that the user could chose a fixed-procedure provided by the system or to create his own computational procedure interactively. Besides this system could accept/output structural model and results from/to graphics/FEM systems such as NASTRAN, CADAM, SUPERTAB etc by the use of standard COMPASS universal file format (C. U. F) and a facility for data file transformation. A special FE model generation ability is also provided. The overlay technique is used in the executive control to lower the computer resources needed to run this program system.

A brief flowchart of this program is shown in Figure 2.

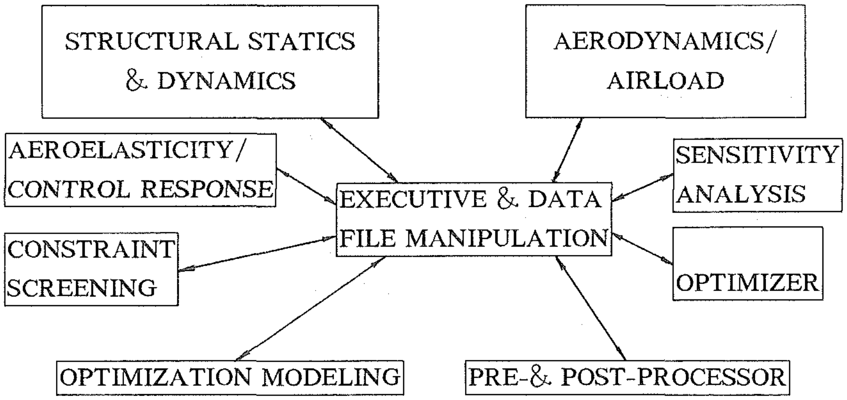


Figure 1. Configuration of COMPASS

Ⅲ. Structural and Sensitivity Analysis

Structural and sensitivity analysis are the basis of optimum design and are the most time-consuming parts of which. The static, dynamic and aeroelastic analysis provide necessary informations for behaviour evaluation of a given composite structure including its displacement and stress/strain states under applied loads, its inherent vibration frequencies and modes, the divergence speed and control efficiencies, and the flutter character under a given flight condition. The sensitivity analysis provides quantitative scale of how sensitive is a particular behaviour to the change of de-

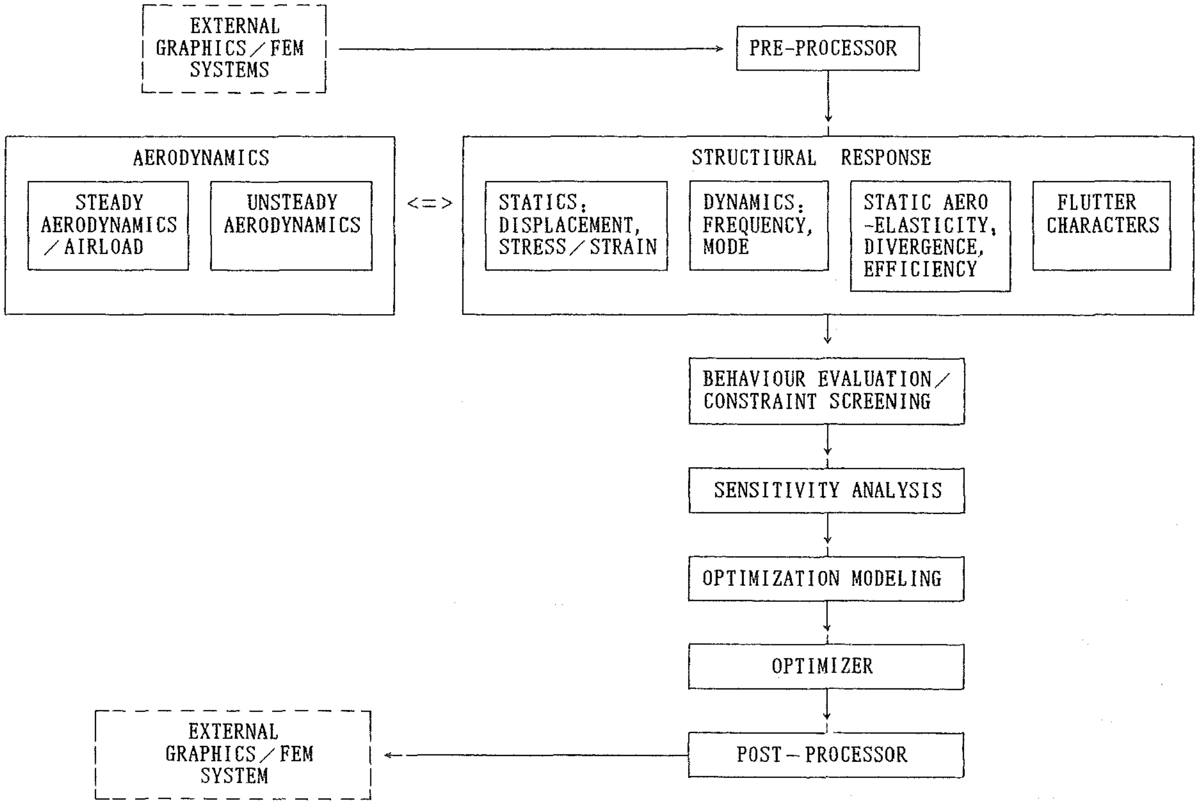


Figure 2 Flowchart of COMPASS

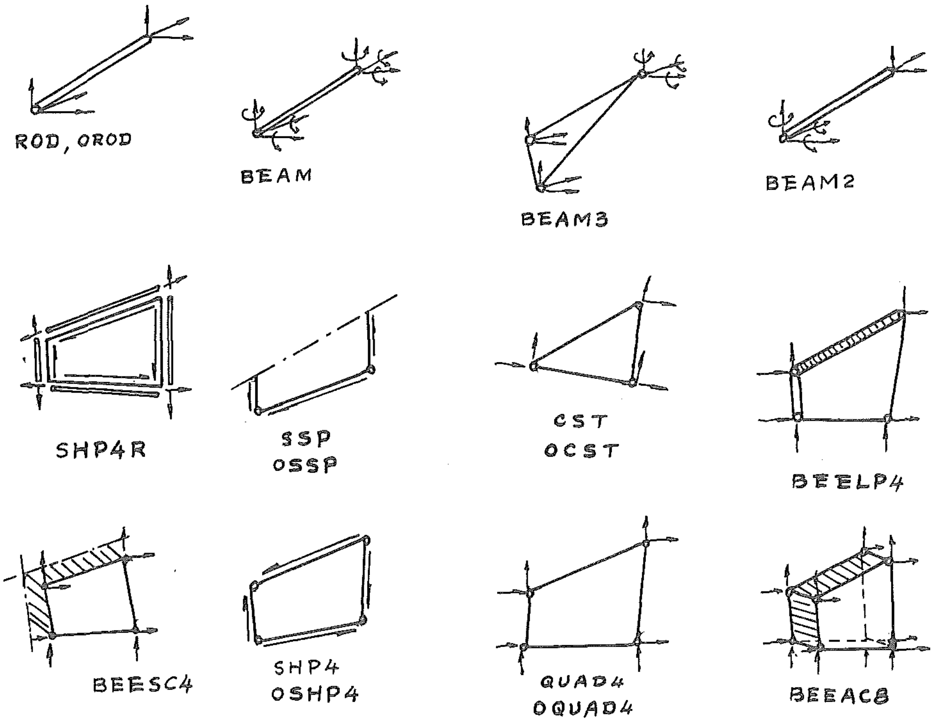


Figure 3 FLement Library

sign parameters (i. e. the design variables). These design sensitivity could be used to chose the most effective way to modify the structure, to construct the explicit approximate model for numerical optimization, to reduce the costly structrual analysis dramatically, and to assist effective structural reanalysis. Some proven effective methods are chosen in the development of the COMPASS[3].

To standardize the operation in finite element analysis and to facilitate the extension of element types in this system, an element library is used with about 17 types of isotropic and anisotropic elements (Figure 3) at present. By the use of this element library the analysis and design on the lamina level of composite laminate could be realized much easier.

The substructuring technique is adapted to improve the computational efficency, to ease the desigh and analysis of structural components by different organizations, to facilitate the local modification of some part of the structure and especially to meet the demands of multiple external store combinations. For static analysis the equilibrium equation, dividing according to the inner and boundary degree of freedom,

$$\begin{bmatrix} K_{ii} & \vdots & K_{ib} \\ \cdots & \cdots & \cdots \\ K_{bi} & \vdots & K_{bb} \end{bmatrix} \begin{bmatrix} U_i \\ \cdots \\ U_b \end{bmatrix} = \begin{bmatrix} F_i \\ \cdots \\ F_b \end{bmatrix} \tag{1}$$

is solved by the well known substructuring method for structural displacement based on the solutions of each substructure and the small boundary degrees of freedom.

For dynamic analysis the eigenvalue problem

$$[C][M]\{q\} = (1/\lambda)\{q\} \tag{2}$$

is solved by the dynamic substructuring (modal synthesis) method; both the fixed-interface and free-interface methods are provided.

In the static aeroelasticity analysis the aerodynamic influence coefficient matrix D is calculated by the kernel function method in aerodynamics module and the efficiencies η and divergence dynamic pressure q are calculated by

$$\eta = -(1/L_R)\{a\}^T[S][D_F]^{-1}\{\alpha_0\} \tag{3}$$

and

$$\lambda\{\Delta\alpha\} = -S_0[C_A][S][D]^{-1}\{\Delta\alpha\} \tag{4}$$

respectively.

The flutter characters are solved by the v-g method from the complex eigen-problem

$$\lambda\{q\} = ([M_{mn}] + (1/k^2)[A_{mn}])^{-1}[\omega_m^2 M_{mm}]\{q\} \tag{5}$$

in which the unsteady aerodynamic force is calculated by the theory of subsonioc lift surface using the spatial souce and sink doublet and vertex lattice method, and the interactions of body are considered. Besides that, the flutter speeds are automatically searched by Laguerre iteration approach.

In view of the accuracy and efficiency, the analysitcal sensitivity expressions for behaviours are derived and their substructuring version are also developed and implemented successfully in COMPASS.

In some cases the differece derivative might be necessary for element and hence the mixed sensitivity analysis scheme will be used sometime. All the formulas for structural and sensitivity analysis are given in ref. 3 in detail.

4. Optimization/ Tailoring Technique

For design tailoring of the composite structures the traditional structural optimization technique should be broadened to including not only weight but also the structural responses or their combination (multiple objectives) as objective, and should be able to consider different mutual contrary behaviour constraints at same time. In COMPASS system the structural weight and all the structural responses such as displacement, stress, strain, inherent frequency, static aeroelasticity efficiencies, divergence dynamic pressure, critical flutter speed etc are treated as the behaviour. Any behaviour or the combination of given behaviours could be chosen as the design objective and the others considered as the constraints. During the design optimization process all the behaviours are evaluated based on the structural analysis; then a optimization mathematical model is constructed along with the behaviour derivatives from sensitivity analysis; this model is then optimized for this design stage by the virtue of optimizer. To release the problems of too much constraints, too much variables and hence too much structural and sensitivity analysis encountered in practical engineering structural optimization, the so called approximation concepts are used in this system. Namely the design process is divided into design stages; the explicit optimization model is created at the begining of each design stage using liear Taylor approximation of behaviours to reduce the costly structural analysis; the constraint screening is performed based on the ε-criteria to select only a few active constraints for optimum search; the variable linking and active variable strategy is introduced to reduce the dimension of design space. In this way only less tens complete structural analysis and sensitivity analysis are normally required for entire optimization for large scale structures with thousands of degree of freedom.

Optimization Model

As mentioned before that any one of the behaviour or the combination of behaviours could be chosen as the objective of optimization and the others are treated as constraints. An explicit approximate model is created at the beginning of each design stage based on the structural and sensitivity analysis. For example when the weight of structure w is selected as the objective a numerical model of wing design could be presented as the following mathematical programming problem:

$$\text{Min } w = \sum_i c_i d_i \tag{6}$$

s. t.

$$\left.\begin{array}{ll} u^* - u \geq 0 & \text{(constr. on generalized displacements)} \\ \omega - \omega^* \geq 0 & \text{(frequency constraints)} \\ V_f - V_f^* \geq 0 & \text{(flutter constraint)} \\ \eta - \eta^* \geq 0 & \text{(static aeroelastic efficiency cons.)} \\ q - q^* - \geq 0 & \text{(divergence dynamic pressure cons.)} \\ \sigma^* - \sigma \geq 0 & \text{(stress/strain constraints)} \end{array}\right. \tag{7}$$

and the upper/lower bounds on design variables

$$\underline{d}_i \leqslant d_i \leqslant \bar{d}_i \qquad i = 1, 2, \cdots\cdots, NDV$$

The design variable $\{d\}$ may be the direct (physical) variable such as the element size (thickness of the panel/layer, area of rod etc.) and the balancing weight, or may be some intermediate variable (e. g. the reciprocal of element size) or even the generalized variable from the variable linking:

$$\{a\} = \{a_0\} + [T]\{d\} \tag{8}$$

here, $\{a\}$ are the direct variables; $\{T\}$ is the transform matrix, the coefficients of which depend on the particular form of variable linking. Some form of the polynomial linking scheme is used in COMPASS.

Numerical Optimization

The optimization model of eqs. (6) and (7) are presented as explicit functions of the design variables by th approximation of behaviour with its first order Taylor expansion at the beginning of each stage. The optimizer of COMPASS provides different candidate algorithms including Sequential unconstrained Minimization Technique (SUMT), Usable Feasible Direction Method (FED), Sequential Quadratic Programming (SQP), Sequential Linear Programming (SLP) and Generalized Reduced Gradient (GRG) method and Augmented multiplier method etc. Due to the approximation nature, an adaptive moving limit strategy is used in conjuction with each optimization to limit the amount of design variation of each variable and to ensure the convergency of design process.

V. Sample Examples

To verify the general applicability of COMPASS for development study and engineering applications many numerical demonstration (including some simplified examples and some with engineering background) has been carried out successfully and some of them are cited below.

Simplified Metal/Composite Wing (Optimum Design)

The simplified wing with composite skin is shown in Figure 4. It is symmetrical about x-o-z and therefore only half structure is treated with total 15 node points. A symmetrical and unbalanced layup of skin with 0°, 45°, −45° and 90° layers are chosen. Two different load cases are considered. All the loads include the inertia loads are concentrated to the node points.

Design optimization for minimum weight under stiffness substitution requirement, static aeroelasticity limits, critical flutter speed, inherent frequency are carried out respectively and shown in Figure 5. The design under all these behaviour constraints is also studied. In these study total 14 design variables are

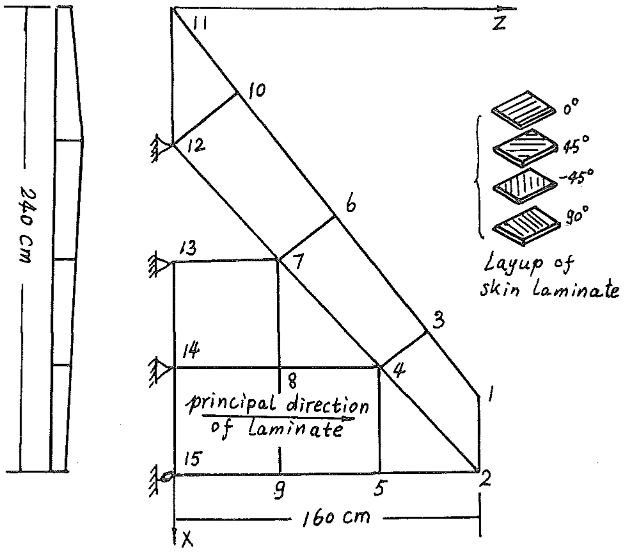


Figure. 4 Simplified Metal/Composite Wing

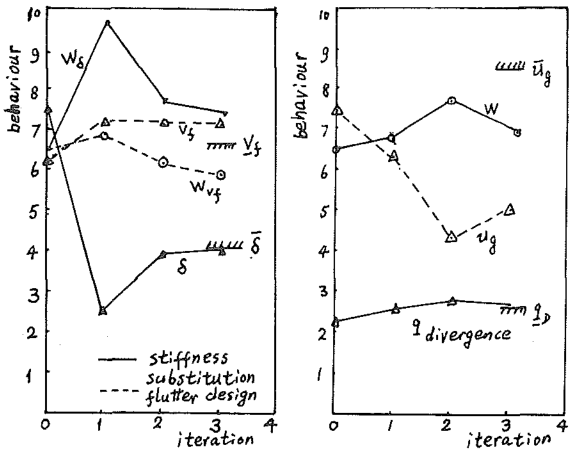
used including eight of them for layer thickness of the composite skins.

Design for Stiffness Substitution

To substitute an existing wing with a composite structure, one of the basic requirements is to meet the criteria of ″stiffness equivalency″. For this reason the deflection limitation of many given points are assigned according to the displacement of the prototype structure. In this example the constrained displacement limit of 4 cm at given point (corresponding to the original metal skin thickness) is defined. From the results obtained (Table 1, Figure 5a), it could be seen that with the same stiffness requirement the metal/composite wing may attain about 31% weight saving within only 4 design iterations.

Static Aeroelasticity Design

Design optimization for improving the static aeroelasticity characters of wing is studied with assigned constraint limits on control efficiency and divergence dynamic pressure. The result (Table 2) is that in only 3 interations the divergence speed has been increased 16% but with only 8% of weight penalty. It might be anticipated that the weight penalty could be further reduced if more design variables are chosen.



a) Single Constraint b) Multiple Constraints

Fig. 5 Interation History of Metal/Composite Wing

Design for Flutter Speed

Flutter is often a dominated factor in wing lift surface design especially in case of wing with external stores. In this study of wing design for critical flutter speed and frequency limits (Table 3, Figure 5a), the flutter speed could increasing about 15% and at the same time with a gain of weight decreasing for about 8% by adjusting the skin parameters properly. It is interested to point out here that the introducing of frequency constraint here has a positive effect to reduce the weight.

Frequency Limited Design

It is a wise way to design a structure with its inherent frequencies beyond a known harmful disturbance frequency band, or to decreasing its dynamic response to a permit level so that to increasing the structural integrity and safety. To verify the ability of COMPASS, this wing is designed under a given lower bound of frequency. It could be found (Table 4) that to increase the lowest frequency about 15% the weight penalty is about 6.5%. An effect design improvement could be obtained with COMPASS in only three design iterations.

Design Under Aeroelasticity and Other Limitations

By the virtue of the mathematical programming methods a variety of mutual contrary behaviour constraints could be considered simultaneously in one optimization round by COMPASS.

In this example all the control efficiency, divergence speed, flutter speed, frequency and generalized displacement constraints are imposed. It should be emphasized here that although these constaints be treated simultaneously no extra design iterations are needed for convergence and no extra weight penalty occures than single behaviour case because the critical constraints are those for static aeroelasticity limits only (Table5, Figure 5b).

Simple composite Wing Box(Case Study)

A simple rectangular composite wing box(Figure6) is used to study the effects of composite layup on the structural responses for the given cases. Only the orientation of the principal direction θ of the symmetrical unbalanced laminate skin is changed and the displacements, inherent frequencies, and flutter speed corresponding to each direction are shown in Figure 7. The tendency of flutter speed variation coincide well with the previous results[7]. It can be seen from the results that at an orientation about $\theta = 35°$ the flutter speed reach the maximum and so is the washout (tip angle of an attack decreasing to the minus maximum).

This example has shown that the case study could be performed by COMPASS with trivial efforts to get valuable results as a guide to engineering aplications.

Engineering Samples

Two examples of wing and tail with engineering background are given in Figure 8 and Figure 9 respectively. All these large scale composite wing structures are of thousand d. o. f. Satisfactory analysis and optimization results on the layer level have been obtained in several design stages[8,9]. The ability of COMPASS for large scale engineering design has been demonstrated.

Summary

An effective structural optimization COMPASS has been developed and put into operation successfully for structural design optimization/tailoring of Composite Structures. Based on the experiences gained it could be concluded that:

1. the superior high specific stiffness and strength and especially its designability of composite do offer attractive possibility to reduce structural weight and improve the aircraft performence; all of these are to be explored by the designers.
2. the design optimization provides necessary ability to tailoring the structural design according to different even mutual contrary requirements at preliminary design stage to improve the structural behaviours through properly selecting of the design parameters (variables);
3. the program system COMPASS is proven to be an effective engineering software for composite structural tailoring(both for case study and engineering design, not only for aeronautical but also for other industries).

Acknowledgements

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Table 1　Stiffness Substitution Design

Behaviour Iteration	Metal/Composite Wing		Metal wing	
	displacement	weight	disp.	weight
0	7.4512	65.372	3.980	108.876
1	2.4291	96.543		
2	2.8416	76.745		
3	3.9933	74.764		
Limit	4.00			

Table 3　Flutter Speed Design

Behaviour Iteration	Flutter Speed V_f, cm/s	Inherent Freq. ω, rad/s	weight w,Kg
0	62817	87.02	65.372
1	72526	97.93	69.930
2	72526	85.02	62.332
3	72526	79.91	59.859
Limit	65000	80.0	

Table 2　Static Aeroelasticity Design
(Control Efficiency & Divergence)

Behaviour Iteration	Efficiency η	Dynamic Pressure q,kg/cm^2	weight w,kg
0	0.921	231.8	65.372
1	0.929	256.5	68.680
2	0.939	270.0	77.076
3	0.918	268.0	70.913
Limit	0.9	268.0	

Table 4　"Dynamic Design" of wing
(Frequency)

Behaviour Iteration	Inherent Freq. ω,rad/s	weight w,ug
0	87.07	65.372
1	101.11	71.148
2	100.01	
	100.00	
Limit	100.0	

Table 5　Design under Multiple Behaviour Constraints

Behaviour Iteration	Efficiency η	Divergence q_D	Flutter v_f	Frequency ω	Displacement ug	weight w
0	0.921	231.8	62817	87.02	7.451	65.372
1	0.928	256.5	62817	91.79	6.395	68.680
2	0.939	270.0	62817	104.55	4.346	77.076
3	0.918	268.4	62817	95.68	5.064	70.916
Limit	0.9	268	56500	80	8.5	

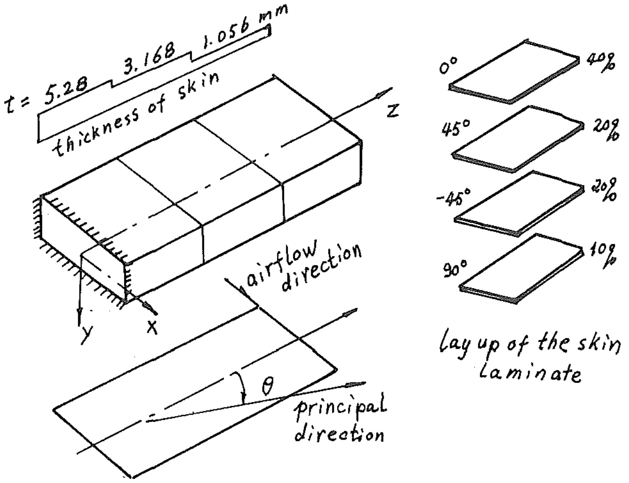

Figure 6 Straight Rectangular Wing

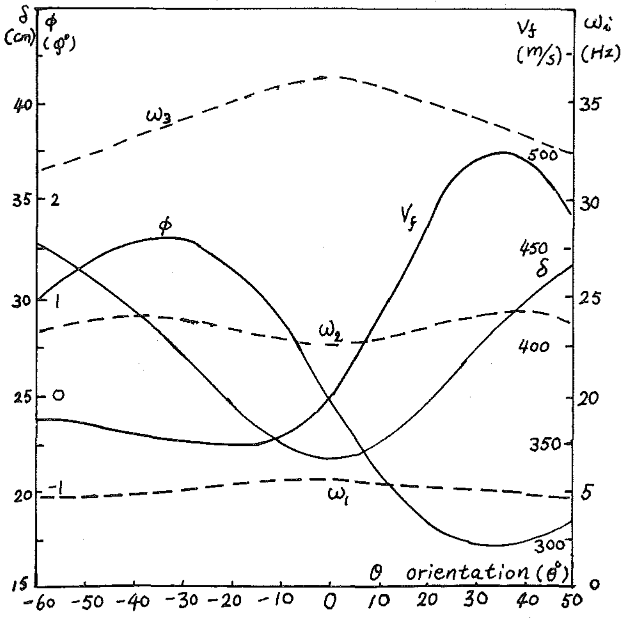

Figure 7 Effects of Fiber Orientation

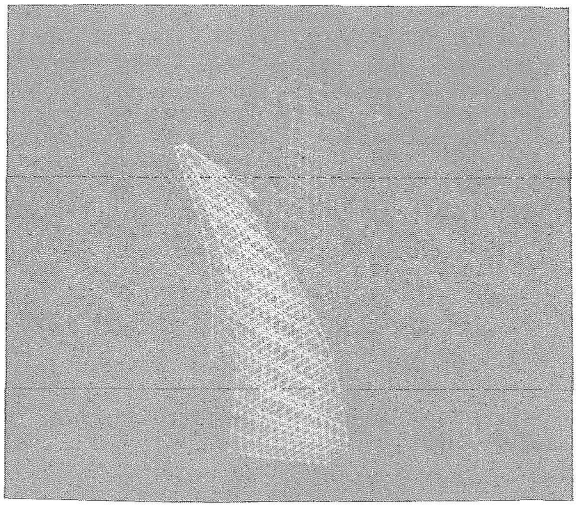

Figure 9 Composite Tail (428 Nodes)

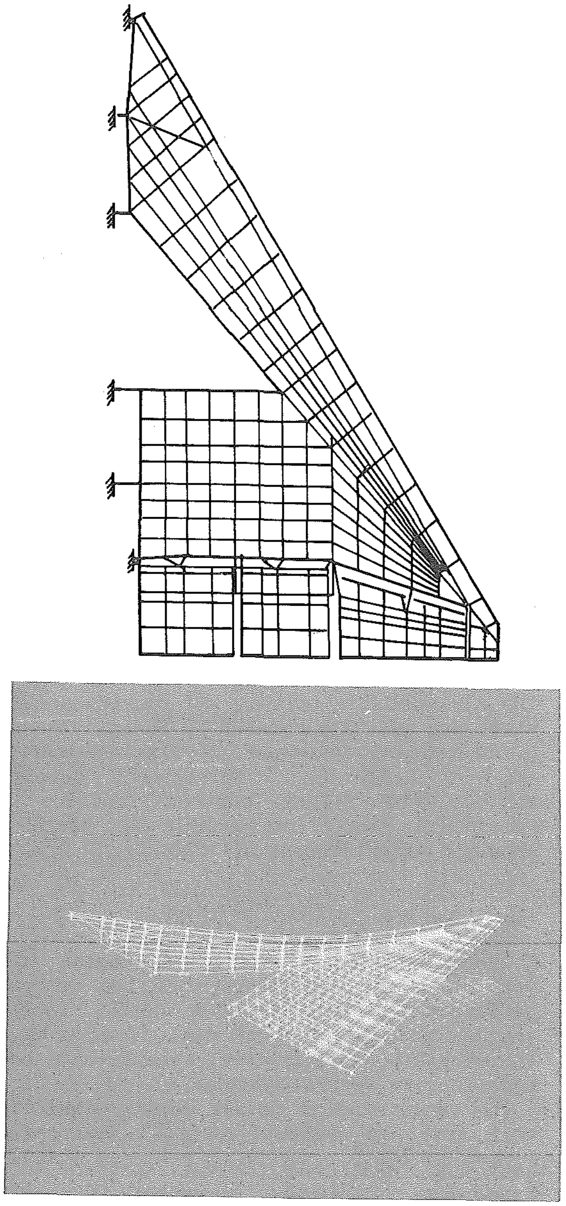

Figure 8 Composite Wing Structure (344 Nodes)