FACTA UNIVERSITATIS
Series: **Mechanical Engineering** Vol. 3, N° 1, 2005, pp. 17 - 29

MINIMUM WEIGHT DESIGN OF THIN-WALLED COMPOSITE STRUCTURES

UDC 519.863 : 693.98 : 531.36

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Abstract. *The aim of the work presented here is to develop an efficient method for the minimum weight design of thin-walled composite structures. A multilevel approach is used for optimization of the structures modeled with layered shell finite elements subjected to stress, system stability and initial failure constraints. The multilevel optimization permits a large problem to be broken down into a number of smaller ones, at different levels according to the type of problem being solved. The optimization method presented here is based on combining optimality criterion (OC) and mathematical programming (MP) algorithms. The finite element analysis (FEA) is used to compute internal forces at the system level. The local stress and local initial failure load in each independent element are defined as component constraints. The use of this MP algorithm is essential to the multilevel approach and local level since it can handle the highly nonlinear component problem, such as local buckling or special initial failure constraints at the mechanically fastened joints. The multilevel algorithm is applied to the minimum-weight design of complex aircraft structures subject to multiple constraints such as aircraft parachute composite beam.*

Key Words: *Optimization, Composite Structures, Multilevel Approach, Optimality Criteria, Initial Failure Constraints, Buckling Constraints*

1. INTRODUCTION

One of the major tasks in the design of aircraft wing structures is the sizing of the structural members to obtain the desired strength, weight, and stiffness characteristics. Optimization algorithms have been coupled with structural analysis programs for use in this sizing process. Most of the difficulties associated with the large structural design are solution convergence and computer resources requirements. Structural optimization problems traditionally have been solved by using either the mathematical programming (MP) or the optimality criteria (OC) approach. More recently, the works in Refs [1-3,14] have illustrated the uniformity of the methods. Nevertheless, each approach offers certain advantages and disadvantages. The MP methods are extremely useful in defining the design problem in proper mathematical terms. When the design variables are few then these

Received October 20, 2005

methods can be used quite effectively for optimization. However, in the presence of a large number of variables these methods are very slow. The rate of convergence for OC methods is initially very fast, step size determination is critically closer to the local optimum where the number of active constraints' increases and the computations of Lagrange multipliers become more complex. Power and weakness of the various MP methods are given in Ref. [8]. Ideally, a methodology that exploits the strength of both approaches could be employed in a practical system. The object of the present research effort is to develop such a design method that can efficiently optimize large structures exploiting strengths (power) of the MP and OC methods. The motivation of this study is to come up with a multilevel optimization method using optimality criteria and mathematical programming techniques. The multilevel optimization permits a large problem to be broken down into a number of smaller ones, at different levels according to the type of problem being solved. This approach breaks the primary problem statement into a system level design problem and a set of uncoupled component level problems. Results are obtained by iteration between the system and component level problems. The decomposition of a complex optimization problem into a multilevel hierarchy of simpler problems often has computational advantages. It makes the whole problem more tractable, especially for the large engineering structures, because the number of design variables and constraints are so great that the optimization becomes both intractable and costly. The nature of an aircraft structure makes multilevel optimization highly practical, not only in terms of reducing the computing cost but also because the individual tasks in the traditional design process are preserved. The suitability of the multilevel optimization in a more complex design problem which is tested on a structure representative of the wing box in composite material, with buckling limitations in each panel and another problem in which reliability requirements are also included. The multilevel approach for optimization of the composite structures subject to stress, displacement, buckling and local failure constraints is developed.

2. Formulation of Optimization Problem

The general structural optimization problem of the layered composite structures modeled by finite elements can be stated as follows:

Find the vector of design variables *x* so that

$$W=\sum_{i=1}^{n}\rho_i l_i x_i \Rightarrow \min \tag{2.1}$$

subject to behavior and side constraints

$$G_j=C_j-\overline{C}_j\geq 0 \quad j=1,...,m \tag{2.2}$$

where: W – is structural weight of structure

x_i – is design variable assigned to element i

l_i – is a geometrical parameter so that product $l_i x_i$ is the volume of element i

ρ_I – is mass density

G_j – is constraint j

$\overline{C}_j$ – is the limiting value of constraint j

n – is total number of elements

m –is total number of constraints.

The constraints imposed on the structure, defined by equation (2.2), may have the global and local character. The global constraints will be defined as system constraints. The system constraints imposed on the structure may include the maximum allowable stress in each element, the displacement limits at one or more locations, system stability, reactive forces, dynamic stiffness, divergence, flutter, etc. In addition to these there would be limitations on the minimum and maximum sizes of the elements.

In addition to system constraints there are local constraints. These include various buckling loads, various failure types in composite structures, etc.

The inclusion of all these constraints in optimization process to large-scale structures is inefficient regarding the computational aspect. However, to develop an efficient algorithm that effectively handles all types of constraints would be impractical and generally unnecessary. In the case of most structures it is likely that one can predict the type of constraint that will be the most active at the optimum and use the algorithm based on that constraint. The multilevel optimization approach may be very efficient for optimizing large-scale structural systems because it breaks the primary problem statement into a system level design problem and a set of uncoupled component level problems. Results are obtained by iterating between the system and local level problems. The decomposition of a complex optimization problem into a multilevel hierarchy of simpler problems often has computational advantages. It makes the whole problem more tractable, especially for the large aircraft structures. The nature of an aircraft structure makes multilevel optimization highly practical, not only in terms of reducing the computing cost but also because the individual tasks in the traditional design process are then preserved.

3. THEORY OF MULTILEVEL OPTIMIZATION

Let D and d represent sets of system component design variables, respectively. Then the problem can be stated as:

Find vectors **D** and **d** so that

$$W(D) \Rightarrow \min \tag{3.1}$$

subject to

$$G_q(D,d) \geq 0\,,\ \ q \in Q \tag{3.2}$$

and

$$g_{lj}(d_j, D) \geq 0\,,\ \ l \in L\,;\, j \in M \tag{3.3}$$

$\mathbf{G_q\ (D,d)}$ represents constraints that are strongly dependent on **D** vector and they are implicit functions except for the side constraints. $\mathbf{g_{lj}(d_j\ ,D)}$ represent constraints that are primarily dependent on j component variables $\mathbf{d_j}$, and they are either explicit or implicit functions of $\mathbf{d_j}$, depending on the type of constraints and the type of local failure analysis. Symbols **Q** and **L** denote the set of system and component level constraints respectively, **M** denotes the number of components and $\mathbf{d^T = [\ d_1^T, d_2^T, ..., d_M^T]}$.

The system design variables can be expressed symbolically as explicit functions of the detailed design variables, that is

$$D_j = \Psi(d_j) \quad j = 1, ..., M \tag{3.4}$$

For each component the number of detailed design variables is larger than that of the corresponding system design variables.

Therefore, casting the problem entirely at the system level by expressing $\mathbf{D_j}$ as functions of $\mathbf{d_j}$ and solving it by using mathematical programming methods are both impractical tasks for large-scale problems. The multilevel approach presented here is decomposed into two levels of design modification; one with the constraints that are strongly dependent on system design $\mathbf{D}$ and the other with the constraints that are primarily dependent on local design variables $\mathbf{d_j}$. Then system and local analyses and optimizations are carried out separately and tied together by an iterative scheme going from one level of design modification to the other and visa-versa seeking an overall optimum design. In Fig. 1 the simplified multilevel optimization process is shown.

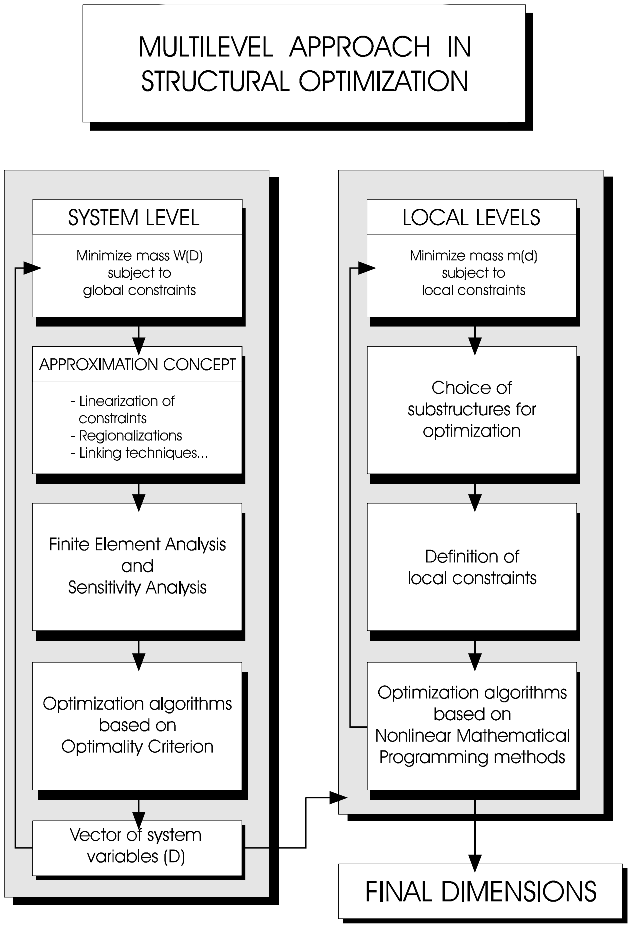

Fig. 1. Multilevel approach in structural optimization

The structural optimization problem given by Eqs. (3.1)–(3.3) is recast as a multilevel optimization problem following form:

i.) System level:

$$\text{Find vector D} \tag{3.5}$$

$$\text{so that } W(D) \Rightarrow \min \tag{3.6}$$

$$\text{and } G_q(D, d^*) \geq 0 \;;\; q \in Q \tag{3.7}$$

where **d*** implies that the parameters strongly dependent on detailed design variables **d** (i.e., failure loads and local buckling) do not change during a system level design modification stage.

ii.) Component level:

$$\text{Find vectors } \mathbf{d_j} \tag{3.8}$$

$$\text{so that } m_j(d_j) \Rightarrow \min \tag{3.9}$$

$$\text{and } g_{lj}(d_j, D^*) \geq 0 \,;\, l \in L \tag{3.10}$$

where **D*** implies that the parameters strongly dependent on the system level design variables are kept constant during each component design modification stage.

4. SYSTEM LEVEL OPTIMIZATION

An efficient optimality criterion method is used for the system level optimization of large-scale complex structures subjected to constrains which are included at the system level. The optimality criteria approach will be used for optimizing the structures with system level constraints. The optimality criteria methods for structural optimization involve:

1. derivation of set of necessary conditions that must be satisfied at the optimum design, and,
2. the development of an iterative redesign procedure that drives the initial trial design toward a design which satisfies the previously established set of necessary conditions.

In order to establish the optimality conditions for the problem defined by (3.5)–(3.7) we need the associated Lagrangian which is given by the expression

$$L(D, \lambda) = \sum_{i=1}^{N} \frac{W_i}{D_i} + \sum_{j=1}^{Q} \lambda_j G_j \tag{4.0}$$

where λ_j's are the Lagrange multipliers. The Kuhn-Tucker optimality conditions are now obtained, in part, by differentiating the Lagrangian and the complete set is given by

$$D^* \text{ is possible} \tag{4.1}$$

$$\lambda_q G_q(D^*) = 0 \;\; \lambda \geq 0, q \in Q \tag{4.2}$$

$$\nabla W(D^*) + \sum_{q \in Q} \lambda_q \nabla G_q(D^*) = 0 \tag{4.3}$$

If the problem is assumed to be convex then these conditions are necessary and sufficient for the solution of vector D^*, λ^* to represent a global optimizing point; otherwise they define a local optimum. The optimum structure must satisfy Eqs. (4.1)–(4.3). These are the Kuhn-Tucker conditions or the optimality conditions. Equation (4.3) is the ratio of the weighted sum of the gradient of the constraints to the gradient of the objective function, which must be equal for all elements in an optimum design. Equations (4.1) and (4.2) ensure satisfaction of the constraint equations. Constraints G_q in equation (3.7) may be displacement limits at the different node points in a structure, the relative nodal displacements corresponding to maximum allowable stress in each element, system stability, frequency constraints, flutter requirements, various failure criteria in layered composite structures such as the Tsai-Wu criterion.

The real optimum structure must satisfy conditions (4.2)–(4.3). To develop a computational algorithm that handles all these constraints efficiently would be difficult and generally unnecessary. In practical design problem what may be required is a design which is near minimum weight and not a design that exactly satisfies the mathematical optimality criteria. This can generally be achieved by designing the structure based on one or two of the must important constraints, and checking the design for the other constraints.

Problem optimization defined by Eqs (3.5)–(3.7) or (2.1)–(2.2) involves: large numbers of design variables, large numbers of inequality constraints and many inequality constraints that are computationally burdensome implicit functions of the design variables. These obstacles have been overcome by replacing the basic problem statement (3.5)–(3.7) with a sequence of relatively small, explicit, approximate problems that preserve the essential features of the original design optimization problem. This has been accomplished through the coordinated use of approximation concepts. The most important feature of the approximation concepts approach lies in the construction of simple explicit expressions for the set of constraints retained during each stage. This is achieved by linearization of these constraints with respect to linked reciprocal design variables. The linearized behavior constraints (3.7) are obtained by using the first order Taylor series expansion as:

$$G_q(D,d^*)=1-\sum_{i=1}^{n} C_{iq} D_i \quad ; i=1,...,Q \tag{4.4}$$

where $\mathbf{C_{iq}}$ is the partial derivative of **q**-th constraint for **i**-th design variable, a **Q** is the total number of constraints. Equation (4.4) represents the current linearized approximations of the retained behavior constraints. Using (4.4) the retained behavior constraints system level optimization problem (3.5)–(3.7) can be expressed as:

Find vector **D** so that

$$W(D)=\sum_{i=1}^{N} \frac{w_i}{D_i} \Rightarrow \min \tag{4.5}$$

subject to constraints

$$G_q(D)=1-\sum_{i=1}^{n} C_{ij} D_i \quad ; q \in Q \tag{4.6}$$

and

$$D_i^L \le D_i \le D_i^U \tag{4.7}$$

$\mathbf{w_j}$ are positive fixed constants corresponding to the weight of the set of elements in the j-th linking group when $\mathbf{D_j=1}$. The set of independent design variables after linking is denoted by N and equation (4.6) represents the linear approximations of the behavior constraints. $\mathbf{D_i^L}$ and $\mathbf{D_i^U}$ respectively denote lower and upper limits on the independent design variables.

In developing the optimality conditions standard approach is to form a Lagrangian:

$$L(D,\lambda)=\sum_{i=1}^{N}\frac{w_i}{D_i}-\sum_{q\in Q}\lambda_j(1-\sum_{i=1}^{n}C_{ij}D_i) \tag{4.8}$$

where λ_q are the undetermined Lagrangian multipliers. Approximation problem (4.5)–(4.7) is convex problem and therefore the Kuhn-Tucker conditions are necessary that solutions D^*, λ^* represent global minimum. The Conventional optimality criteria methods for structural optimization involve: (i) the derivation of a set of necessary conditions that must be satisfied as the optimum design and (ii) the development of an iterative redesign procedure that drives the initial trial design toward a design which satisfies the previously established set of necessary conditions. Each approximate primal problem of the form given by equations (4.5)–(4.7) can be transformed to correspond to an explicit dual problem. Detail solution methods and optimization algorithms are given in Refs [8,9].

4.1 Definition of Strength Constraints in Layered Composites

For analysis and optimization fibrous layered composite structures, modeled by orthotropic membrane finite elements, various failure criteria can be used. The Tsai- Wu criterion is frequently used for failure analysis of orthotropic layers in composite stack. This criterion can be expressed as:

$$T_t=[(\frac{\sigma_1}{F_1})^2+(\frac{\sigma_2}{F_2})^2-(\frac{\sigma_1\sigma_2}{RF_1F_2})+(\frac{\tau_{12}}{F_{12}})^2]^{1/2} \tag{4.9}$$

where σ_1, σ_2, τ_{12} are the components of stress tensor σ; F_1 ,F_2 and F_{12} are the stresses of failure in uniaxial tension, compression and shear, respectively and T_t is Tsai's number. By using eqns (4.6) and (4.9) the linearized approximations of Tsai-Hill criterion can be written as:

$$G_q=1-\sum_{i=1}^{n}\frac{\partial T_t}{\partial D_i}D_i \tag{4.10}$$

where:

$$C_{iq}=\frac{\partial T_t}{\partial D_i}=T_1\frac{\partial\sigma_1}{\partial D_i}+T_2\frac{\partial\sigma_2}{\partial D_i}+T_3\frac{\partial\tau_{12}}{\partial D_i} \tag{4.11}$$

with

$$T_1=\frac{1}{2T_t}\frac{2\sigma_1-\sigma_2}{(F_1)^2}$$

$$T_2=\frac{1}{2T_t}[\frac{2\sigma_2}{(F_2)^2}-\frac{\sigma_1}{(F_1)^2}]^2 \text{ and}$$

$$T_3=\frac{1}{T_t}\frac{\tau_{12}}{(F_{12})^2}$$

Similarly, the linearized constraints such as displacement, stability, frequency or other system constraints can be defined.

5. LOCAL LEVEL OPTIMIZATION

Local level optimization process can include various types of failure modes in laminates or local buckling constrains. This optimization problem is solved by algorithms based on nonlinear mathematical programming methods. Classical optimization problem in local level are mechanically fastened joints in composites. Initial failure arises on a characteristic curve, as shown in Fig. 2.

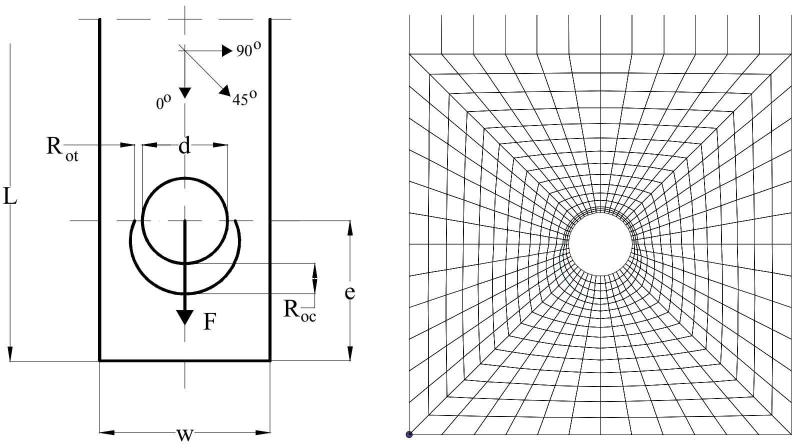

Fig. 2. Description of the Characteristic Curve with FE Mesh

The characteristic curve with finite element mesh, Fig. 2, is specified by the expression:

$$r_F(\Phi)=\frac{D}{2}+R_t+(R_c-R_t)\cos\Phi \; ; -\frac{\pi}{2}\leq \Phi\leq\frac{\pi}{2} \tag{5.1}$$

where $\mathbf{R_t}$ and $\mathbf{R_c}$ are referred to as the characteristic lengths for tension and compression. In order to determine the load at which a mechanical fastened joint fails and the mode of failure, the conditions for failure must be established. In this paper the joint is taken to have failed when certain combined stresses have exceeded a prescribed limit in any of the plies along the chosen characteristic curve. The combined stress limit is evaluated using the failure criterion proposed by Yamada- Sun in form [11]

$$\left(\frac{\sigma_1}{F_1}\right)^2+\left(\frac{\tau_{12}}{F_{12}}\right)^2\leq 1 \tag{5.2}$$

where σ_1 and τ_{12} are the longitudinal and shear stresses in a ply, respectively (1 and 2 being the directions parallel and normal to the fibers in the ply). F_{12} is the rail shear strength of a symmetric cross ply laminate $[0^o/90^o]_s$. F_1 is either the longitudinal tensile strength or the longitudinal compressive strength of a single ply.

This criterion is based on the assumption that just prior to failure of the laminate, every ply has failed due to cracks along the fibers. It is very important to say that local constraints such as expressed by Eq. (5.2) or similar, can be included in the optimization process as direct formulae using the Fortran lingue notation in programme OPTIS [12].

The direct manner for defining very nonlinear constrains by using the direct Fortran description is very efficient in practical optimization of composite or metal aircraft structure. Final dimensions are obtained at local optimization. Optimization algorithms are based on Nonlinear Mathematical programming methods such as: SUMT, CONMIN, method inscribed hyperspheres [6], etc.

6. NUMERICAL EXAMPLES

To illustrate the application and versatile multilevel approach to the weight structural optimizations composite structure subjected static loads are considered.

6.1 Optimum Design of Layered Composite Panel

As standard model for the weight minimization fibrous layered composite panel is considered. Ply's orientations for optimization of panel are [**0°**/ +**45°**/ **–45°**/ **90°**]. This example involves three distinctive loading conditions, Table 1. Material properties of the panel are given in Ref. [10]. The weight minimization carried out for Hill-Tsai, buckling and lower limits in membrane stiffness criteria. In this case the buckling constraints at local level are considered. The basic analysis concepts for buckling constraints are presented in Ref. [6,15] for a simply supported equivalent homogeneous orthotropic plate with planform dimension a,b subject in plane loading conditions. Fig. 3 shows geometry and loads of the panel.

Lower limits on membrane stiffness are:

$A_{11}(\min) = 0.75 \times 106$; $A_{22}(\min) = 0.5 \times 106$; $A_{66}(\min) = 0.5 \times 106$

Material is graphite/epoxy: **HT-S/4617**:

$E_{11} = 20 \times 10^6$; $E_{22} = 1.3 \times 10^6$; $G_{12} = 0.65 \times 10^6$; $\nu_{12} = 0.304$, $t_{layer} = 0.05$

$F_1^t = 165 \times 10^3$; $F_2^t = 8 \times 10^3$; $F_{12} = 16 \times 10^3$; $F_1^c = 11\ 5 \times 10^3$; $F_2^c = 30 \times 10^3$.

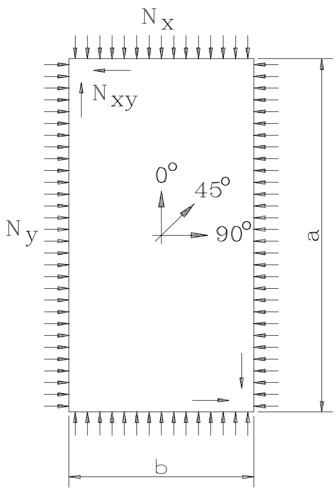

Fig. 3. Model of Layered Composite Panel

The panel is small one optimization problem. It can be consider at one or two levels, with different or the same optimization algorithms. The results obtained by multilevel optimization procedure are the same as those reported in Ref. [10] with respect to weight, thickness distribution and critical constraints

Table 1. Loads of Composite Panel

Load Conditions (k)	N_{xk}	N_{yk}	N_{xyk}
1	8000	0	4000
2	0	8000	4000
3	0	–4000	–2000

Table 2: Optimization Results of the Layered Composite Panel

Available	Orientations	Present Results		Ref . [10]	Number of Layers
i	Θ_i	Initial thickness	Final thickness'	Final thickness'	
1	0^0	0.0714	0.0308	0.0304	7
2	$+45^0$	0.0714	0.0885	0.0898	18
3	-45^0	0.0714	0.0885	0.0898	18
4	90^0	0.0714	0.0324	0.0304	6
		0.2856	0.2402	0.2403	

Table 2 gives the final results obtained by the present method as well as the results reported in Ref. [10].

6.2 Optimization of Aircraft Parachute Composite Beam

As very illustrative example for multilevel optimization procedure the fibrous composite parachute beam considered. The structure of parachute beam shown in Fig. 4 idealized with membrane finite elements. The elements consist of four layers in the 0^o,90^o and $\pm45^o$ directions. The 0^o fibers are parallel to the length of the beam. The parachute composite beam was subject to static loading conditions. The aircraft parachute composite beam shown in Fig. 4 used for system level optimization.

Fig. 4. Parachute CFC-composite beam

Material of composite beam was graphite/epoxy NCHR 914/34%/132/ T300 with next mechanical properties:

E_{11} = 126800	MPa		F_{11}^{t} = 1362	MPa
E_{22} = 9220	MPa		F_{11}^{c} = 1333	MPa
E_{33} = 9220	MPa		F_{22}^{t} = 42	MPa
G_{12} = 4620	MPa		F_{22}^{c} = 172	MPa
G_{23} = G13 = 720	MPa		F_{12} = 100	MPa

$\nu_{11} = \nu_{13} = \nu_{23}$

t_{layer} = 0.13 mm

There are four mechanical fastened joints (holes) at the end of the parachute beam. The loads are introduced in these holes. The zone around each hole is considered as a substructure. This substructure has a characteristic curve, as defined in Fig. 2, which is modeled by very refined finite element mesh. The substructure (rectangular panel with central hole) is treated as an optimization model on the local level. The Yamada-Sun criterion (5.2) around the characteristic curve (5.1) is used as constraints in local level optimization. For this purpose, in the local level, the SUMT optimization algorithm is used. Optimization results of this substructure are thickness of layers:

$t_1(0^o)$ = 2.08 mm
$t_2(+45^o)$ = 0.78 mm
$t_3\,(-45^o)$ = 0.78 mm
$t_4\,(90^o)$ = 0.26 mm

Failure load that is in this analysis obtained: **F_f = 2297 daN**. Failure was initiated in layer 0^o, with extension type of mechanism of failure $75^\circ \le \Theta_f \le 90^\circ$.

Failure loads that are experimentally obtained: (**F_1 = 2087 daN**, **F_2 = 2296 daN** and **F_3 = 2390 daN**).

Good agreement between numerical and experimental results is evident. Detail comparisons between numerical and experimental results are given in Ref. [13]. Difference between numerical and experimental results is maximum 5%.

In this study optimization only the results of one substructure are presented. These results illustrate multilevel optimization process.

7. CONCLUSION

The obtained results demonstrate the practicality of multilevel optimization approach in the design of the complex aircraft structures. In this study two-level optimization algorithm is applied; system- and component level. From the various investigated test problems it becomes clear that the choice of various optimization algorithms at each level plays a major role in the efficiency of the whole optimization process. The presented multilevel optimization approach uses optimality criteria's algorithm in conjunction with the Sequential Unconstrained Minimization Technique (SUMT). The optimality criteria's algorithms are used for system level optimization i.e. in case of weight minimization subject to global (system) constraints that can be displacements, system stability, frequencies, flutter, etc. The Nonlinear Mathematical Programming optimization algorithms are used for local (component) level optimization. Combining FEA, approximation concepts and

OC or dual algorithms has led to a very efficient method for the minimum weight sizing of large-scale structural systems. The proposed method is suitable for designing practical large scale structures with a large number of design variables. Finally, the minimum weight designs obtained for the aircraft parachute composite beam illustrate the application of the multilevel approach to a relatively large structural system.

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MINIMIZACIJA MASE TANKOZIDNIH KOMPOZITNIH STRUKTURA

Stevan Maksimović

Primarni cilj rada je uspostavljanje efikasnog metoda za minimizaciju mase tankozidnih kompozitnih struktura. Za optimizaciju strukture koja je modelirana konačnim elementima ljuski sa ograničenjima u pogledu napona, elastične stabilnosti i inicijalnih otkaza korišćen je višestepeni pristup. Višestepeni pristup optimizacije pretpostavlja da se veliki strukturalni sistem razbije u veći broj manjih strukturalnih sistema sa različitim nivoima u skladu sa tipom razmatranog problema.

Metod optimizacije prezentovan u radu zasnovan je na kombinaciji algoritama na bazi kriterijuma optimalnosti (OC) i nelinearnog matematičkog programiranja (MP). Analize na bazi metode konačnih elemenata (FEA) su korišćene za određivanje unutrašnjih sila na sistemskom nivou optimizacije. Lokalni naponi i opterećenja kod lokalnih inicijalnih otkaza u svakom nezavisnom elementu su definisana kao ograničenja na nivou strukturalne komponente. Korišćenje ovog MP algoritma na lokalnom nivou je suštinski za višestepeni pristup pošto je isti u stanju da opiše veoma nelinearna ograničenja takva kao što su lokalni gubici stabilnosti ili specifična ograničenja inicijalnih otkaza kod mehaničkih spojeva kod kompozitnih struktura. Višestepeni algoritam optimizacije je primenjen u radu na minimizaciju mase složene avionske strukture kao što je to greda kočionog padobrana napravljena od kompozitnih materijala zaslučaj većieg broja ograničenja.

Ključne reči: *Optimizacija, kompozitne strukture, višestepeni prisup, kriterijumi optimalnosti, ograničenja sa aspekta inicijalnog otkaza, ograničenja sa aspekta gubitka elastične stabilnosti.*