OPTIMIZATION METHODOLOGY OF COMPOSITE PANELS

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ABSTRACT

This paper deals with mass optimisation of composite laminates aeronautical structures. It focuses on the final stage of the process of composite structure design i.e. defining the lay-up evolution all over the panel, this being directly used for manufacturing. Strength criteria (in-plane behaviour) and stability criteria (out-of-plane behaviour) performed with appropriate industrial tools are evaluated in the multi-level optimisation presented hereafter. The methodology consists in five steps. In the first two steps, optimisation is performed with continuous variables and a homogenized material (i.e. with approached out of plane properties). In the third step, a lay-up table is selected (or built) and translated into a "continuous" material (i.e. out of plane stiffnesses expressed as continuous variables of the lay-up thickness). In the fourth step, optimisation is performed with the "continuous" material. In the last step, a genetic optimisation is used to round off at discrete ply thicknesses. This methodology provides a manufacturable result (in terms of ply continuity) that satisfies all stress and stacking sequence constraints.

INTRODUCTION

At the moment, civil aeronautic companies improve aircraft capabilities by extensively using high performance composite materials to reduce structure weight. This upward trend in using composite materials leads to develop new methodologies of designing and optimizing current composite parts of an aircraft.

This article is interested in the sizing of a typical elementary part of an aircraft structure: a structural panel (figure 1) made of several bays.

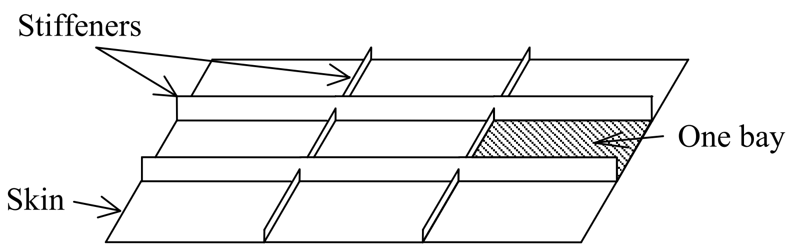


Figure 1: sketch of a structural panel

To optimize this type of panel several discrete design variables and constraints per bay are necessary to describe its geometry and stacking sequence. As a consequence, a one shot global optimization with all variables is difficult to perform.

To avoid this heavy combinatory optimization problem, Liu and Haftka [1] proposed to work with a multi-level approach. Firstly, the total number of stacks (a stack consists of two plies: $0°_2$, $90°_2$ and +/-45°) is optimized all over the structure. This optimization is made with continuous design variables and afterwards rounded off to have a result in terms of ply numbers. In a second time, for each local panel a Genetic Algorithm (GA) is used to find the best stacking sequence. However the result of this optimization does not meet blending laminate requirements: locally optimal stacking sequences don't satisfy lay-up continuity all over the panel. Then, in a second paper [2], they proposed to implement a continuity constraint at the first level of optimization. The use of this constraint allows converging to a solution with a better continuity but still it seems no realistic to find a perfect blended laminate all over the panel.

D. B. Adams, O. Serasta and al. [3-4] developed another approach that deals with "guide based design". This methodology reduces the search space by imposing perfectly outwardly or inwardly blended laminates from a guide stacking sequence. In fact, there is one stacking sequence (the guide) for the complete panel but some plies are not activated (at the top or at the middle of the laminate) to adjust the thickness during the optimization for each local panel. By reducing the design space (simplification of ply drop-off position), it allows to make an optimization in one shot with GA and on a wing-type structure. The GA optimizes the stacking sequence guide (hence the name "Guide Based Design") whereas the fitness function includes a one-dimensional optimization of ply number for each local panel. This methodology seems very attractive but remains limited to a specific ply-drop-off process.

In this paper, we develop a methodology to optimize a composite panel composed of several areas with different thicknesses. This methodology ensures the ply continuity all over the panel without any specific ply-drop-off process. This methodology is composed of 5 steps and addresses an industrial type sizing process.

PANEL SIZING

Material and lay-up consideration

In this study composite panels are made out of stacking pre-preg plies with ply angles limited to 0°, 45°, -45° and 90°. On large areas, laminate is as much as possible balanced (thickness at 45° is equal to thickness at –45°) and symmetric.

In the first time of the sizing of an aircraft panel, laminates are not exactly defined: i.e. lay-ups remain unknown. So, the plate behavior of laminate can only be defined as a homogenized material, generally called "black metal". In-plane stiffnesses depend on the number of plies per angle and are calculated through Classical Laminate Theory (CLT) approach. The bending stiffnesses are worked out from the in-plane behavior and total thickness of the plate; so there are no in-plane/out-of-plane coupling and bending/torsion coupling. When the lay-up of the laminate is known, whole in plane, out-of-plane and coupling plate behavior is calculated through CLT. So, this more exact data can be used to size the panel (more especially in buckling).

Lay-up tables are used to define the stacking sequence for every thickness of the panel. Two rules manage a lay-up table. First, if two areas have the same number of plies, they do have the same stacking sequence. The second one is the "continuity rule". It expresses the fact that if the total thickness increases (by adding one or several plies) then it is not possible to stop a ply at the same time.

Sizing criteria

To size an aircraft panel in current area of a bay (without specific loads or holes), three criteria have to be checked in the form of a Reserve Factor (noted RF – equation 1).

$$RF=\frac{Allowable\ Load}{Effective\ Load}\geq 1 \qquad (1)$$

Damage tolerance ($RF_{Damage\ Tolerance}$)
The Damage Tolerance Criterion checks whether the composite structure damaged by an impact (bird, tool…) is still able to sustain the loads. Used as a constraint in our optimisation scheme, it is directly calculated by an Airbus France software based on experimental data.

Reparability ($RF_{Reparability}$)
During sizing time, stress men have to anticipate potential damages on the structure and so to anticipate the ability to repair the structure. On this type of panel, repair is planned to be done with a plate fixed by a fastener. So the reparability criterion is based on a "fastener hole" calculation.

Stability ($RF_{Stability}$)
In sizing, stability is tackled by a linear Finite Element Model (FEM) calculation. The complexity of the numerical model depends on the part of structure under study, the bay being the smallest one.

Loading
From a coarse finite element model calculation of a global structure (for example: an entire aircraft), called LEVEL 1 model, stress flows are extracted for each finite element of the panel. Then, a selection is made between all load cases to find out the most critical load cases for each criterion. These critical load cases are used to optimize the panel.

OPTIMISATION METHODOLOGY

The methodology is composed of 5 steps with strong links between each step. On the table 1, a sum up of the methodology is shown.

	Description	Results
Step 1	**Pre Thickness law optimization** With homogenized Material	**$t_{0°}$, $t_{45°}$ and $t_{90°}$** (Angle thickness) For each area of the panel
Step 2	**Angle percentages consolidation** With homogenized Material	**t_{Total}** (total thickness) **and Angle percentages** All over the panel
Step 3	**Lay-up table**	**Lay-up table** (stacking sequences dissociated from geometry)
Step 4	**Thickness law optimization** With laminate from lay-up table	**t_{Total}** associated with lay-up table
Step 5	**Round off** With laminate from lay-up table	**Stacking sequence** For each area of the panel

Table 1: Methodology in 5 steps

The purpose of this methodology is to answer to the problem with an industrial point of view: efficient optimization link to manufacturing problem in terms of ply continuity.

Step 1: Pre thickness law optimisation
At this stage the aim is to define what percentages of plies per angle are optimal all over the panel. No constraints are required on angle percentages between the different areas. The optimization problem can be stated as:

Minimize the total mass of the panel

Variables: $t_{\theta°}$ (thickness of θ° plies: [0°, 45°, 90°], with $t_{45°}$=$t_{-45°}$)

Constraints:

- Sizing criteria have all to be satisfied (see above)
- Limitations on angle percentages: %θ°Є [15%, 55%]

Material: homogenized with free angle percentages
Algorithm: gradient based, continuous variables

The results of this optimization are post-treated to obtain 3 curves that express angle thickness for each angle (t0°, t45° and t90°) as a function of total thickness. To respect the continuity rule means to have three increasing functions.

Step 2: Consolidation of angle percentages

When, angles percentages are defined all over the panel, a consolidation of optimization can be done. This optimization with fixed angles percentages is interesting for stress men to have intermediate results during the sizing process. The optimization problem can be stated as in step 1 but material has fixed angle percentages as function of total thickness:

Minimize the total mass of the panel
Variables: t_{Total} for each area (total thickness)
Constraints: sizing criteria are all satisfied (see above)
Material: homogenized with fixed angle percentages function of total thickness
Algorithm: gradient based, continuous variables

Results of this optimization are total thicknesses all over the panel associated with feasible angle percentages.

Step 3: Lay-up table optimisation

The optimized lay-up table has to satisfy the angles percentages targets coming from the previous step and several stacking sequence rules from airbus experience. A genetic algorithm has been developed to optimize this table [5]. In this study, the lay-up table has been defined by a specialist with respect to lay-up constraints. It is important to note that the use of lay-up table in the next steps satisfies completely laminates blending requirements.

Step 4: Thickness law optimisation

With the lay-up table, the laminate behavior is completely described as a function of the total thickness. More precisely, each extension, extension-bending coupling and bending plate stiffness coefficients are calculated as functions of total thickness through the lay-up table to get what is called a "continuous material".

A new optimization is then performed to adjust total thicknesses of the panel in accordance with the new laminate behavior. This optimization problem can be stated as in step 2 but with the "continuous material".

Step 5: Round-off at plies numbers

At this level, it is just needed to adjust the thickness found in the previous step of optimization into a number of ply.

A methodology based on standard genetic algorithms (noted GA) was applied to the rounding-off. The design variables space is not very large because previous steps have reduced it. Indeed only two choices for the number of plies are possible for each area of uniform thickness: the upper and lower round off.

The optimisation problem can be stated as:

Minimize the total mass of the panel
Variables: N_{Total} for each area (Total ply number - values: $^{+}/_{-}$ 1 ply)
Constraints: sizing criteria are all satisfied (see above)
Material: issued from the lay-up table
Algorithm: Genetic with discrete variables

APPLICATION OF THE METHODOLOGY

This chapter presents an application of the complete methodology to the simplest model (one bay). Studies were performed taking into account the three criteria and for one load case. The plate is considered as simply supported on its four edges. This bay is divided in 8 areas of uniform thickness. The aspect ratio is around 0.27. Two studies were achieved with a different load case to demonstrate the ability to optimize with different criteria. On Figure 2 (a and b), both load cases are sketched. Arrows are representative of the in-plane stress flow levels.

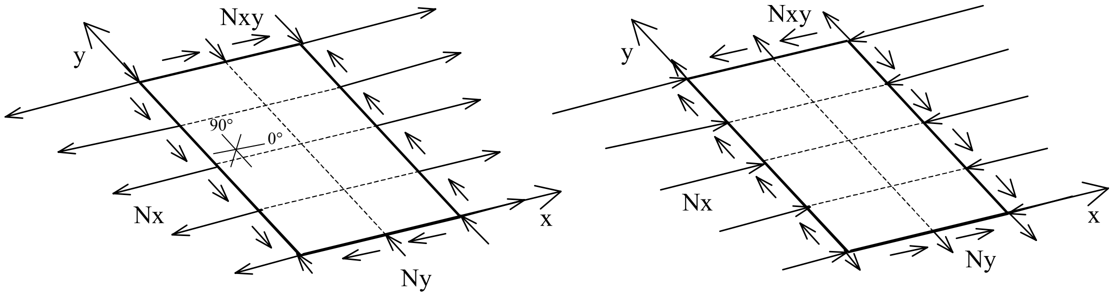


Figure 2: a – Load case in study one – b – Load case in study two

First Study: Panel optimisation with sizing in-plane criteria

In this study, tension stress flow under x direction largely dominates both other flows. Therefore, in-plane criteria are the most critical and pilot the sizing of the bay.
Results of each optimization step are summed-up in figure 3.

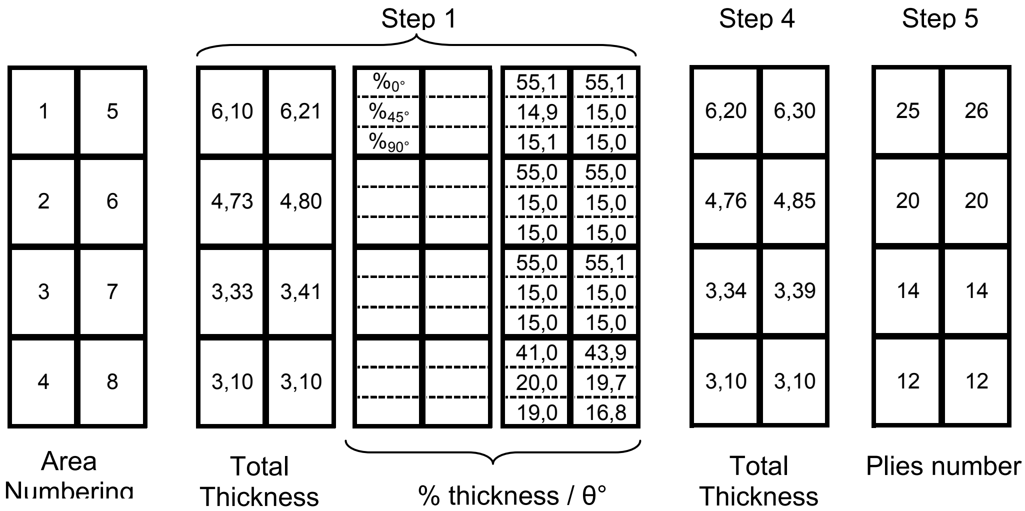


Figure 3: Results of optimisation of the first study

First step: Pre-Thickness law optimisation

The starting point of this optimization is a laminate with no-preferential angle ($\%_{0°}$ = $\%_{45°}$ = $\%_{90°}$ = 25%) and with a uniform thickness of 8 mm.
In addition of the figure 3, another optimization results are important:

- $RF_{Damage\ Tolerance}$ and $RF_{Stability}$ are largely satisfied (RF>>1)
- $RF_{Reparabilty}$ are active (RF~1) for areas 1, 2, 3, 6 and 7
- Normalized mass: 0.544 (Normalized to starting mass)

Post-treatment of these results is quite easy. It indicates a panel with uniform proportions ($\%_{0°}$ = 55, $\%_{45°}$ = 15 and $\%_{90°}$ = 15). Angle percentages of areas 4 and 8 are not taken into account because 3.1 mm is the minimal total thickness imposed by the designers and because RFs are not active in both of these areas.

Second step: Angle percentage consolidation
Here the result of step 2 with $\%_{0°} = 55$, $\%_{45°} = 15$ and $\%_{90°} = 15$ angle percentages is the same as for step 1.

Third step: lay-up table
The lay-up table is built with respect to angle percentages targets [5]. The lay-up table defines stacking sequences from 10 plies to 26 plies with a ply thickness of 0.25 mm which covers largely the thickness range obtained from previous steps of optimization.

Fourth step: Thickness law optimisation
Total thicknesses of step 1 are used as an initial point of this optimization. At this step, stacking is known. Then, the “continuous material” is used to calculate the criteria. Optimized and normalized mass is 0.548 (close to Step1).

Fifth step: Round-off
The sizing criterion of the panel is the local reparability criterion (others are not active). The lowest minimal thickness for each area of the bay has been determined in the former step. So, the use of GAs is not necessary and the thickness can be directly round off at the upper number of plies. However area 4 and 8 are round off at the lower number of ply because a minimal ply number is imposed by designers and. no criteria are active Optimized and normalized mass is 0.559.

Conclusion of the first study
On this study, ability to optimize a panel under in-plane criteria is demonstrated together with the flexibility of the proposed methodology. Indeed several simplifications were achieved during the course of this process. Only in-plane criteria and one set of uniform angle proportions were considered from step 1, as a consequence step 2 was skipped. 5th Step was simplified even avoiding the use of GAs.

Second Study: Panel optimisation under out-of-plane criteria
In this study, compression flow under x direction largely dominates both other flows. Due to panel geometry, stability criterion is the most critical ones. Others criteria are not activate all along the study.
Results of each step of optimization are summed-up in figure 4.

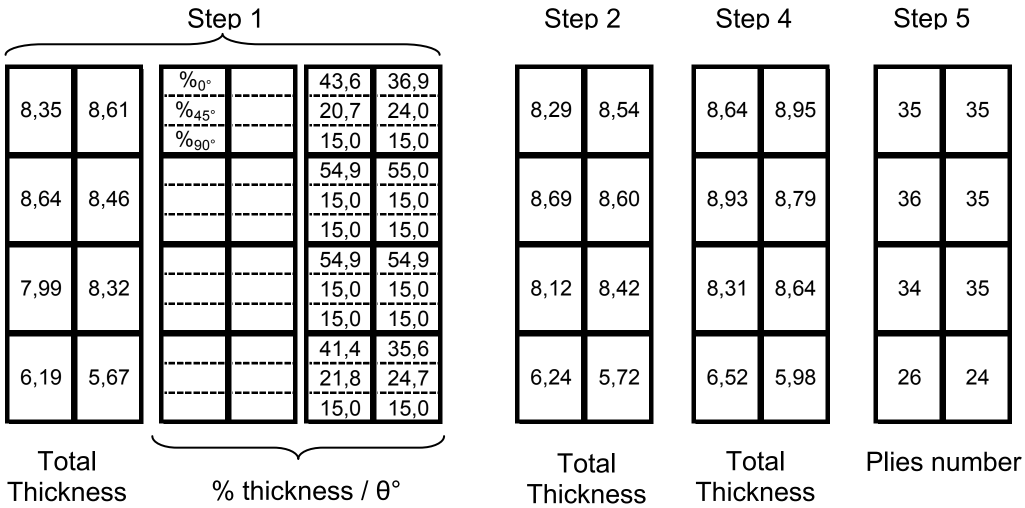
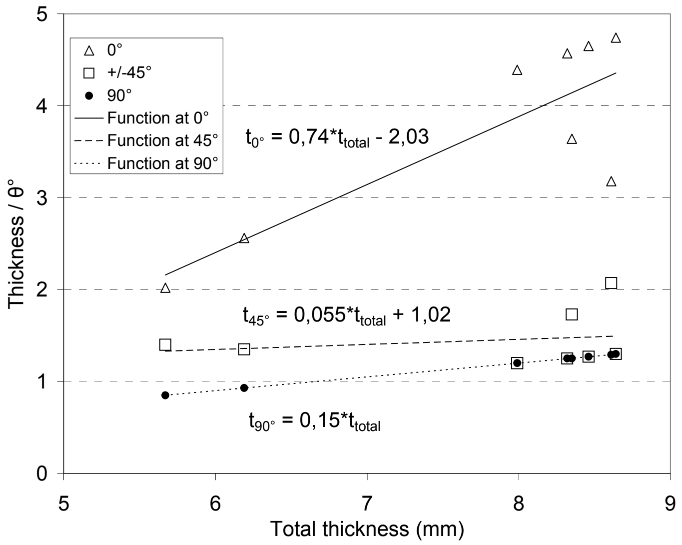


Figure 4: Results of optimisation of the second study

First step: Pre-Thickness law optimisation

Results show a spatial distribution of optimal angle percentage: in the middle of the bay (area 2, 3, 6 and 7), plies at 0° are to be the most numerous whereas in the top and bottom, their proportions reduce to 35% - 45% favoring the presence of plies at +/-45°. In the bay corners, bending stiffness is mainly carried out by +/-45° fibers; in the middle it is achieved by the plies at 0°. Optimized and normalized mass is 0.778.



Graph 1: Angle thickness in function of total thickness

Theses results provide angle thicknesses that do not agree with continuity constraint (see previous chapter): for example, we can see that for two areas (1 and 7), total thicknesses are close but thicknesses at 0° are different.

In this study, a linear regression is done for each angle thicknesses (see graph 1). It can note that functions are defined increasing to satisfy continuity constraint for the next optimization steps.

Second step: Angle percentage consolidation

This step of consolidation evaluates the effect of angle thickness smoothing by linear functions. Logically, mass increases compared to the previous step but here the difference is not large: 0.8% (optimized and normalized mass being 0.784). It can be explained by the good correlation between optimized point (step 1 results) and linear function.

Third step: lay-up table

As for the previous study, this step is not detailed. Number of ply in the table ranges from 20 to 38 with a thickness ply of 0.25 mm.

Fourth step: Thickness law optimisation

Between step 2 and this step, the optimized mass increases by more than 3%. It shows the necessity to take into account the stacking sequence to obtain a valid panel in term of stability criteria. Optimized and normalized mass is 0.810.

Fifth step: Round-off
Because stability is the active criteria, round-off problem is a combinatory one. GA is used. It reduces the number of calculations from 256 possibilities (2^8 combinations) to around only 45 calculations. Optimized and normalized mass is 0.813.

Conclusion of the second study
This study shows that optimising with an active stability criterion is more complex than with in-plane criteria. It demonstrates the interest of each step of the methodology. Another complementary aspect is that with stability criterion continuous optimizations converge slower than with in-plane criteria. A reason for this can be in the sensitivity of stability RF to all thickness variables of the 8 bay areas instead of the in-plane criteria computed per area of the bay.

CONCLUSION
This paper demonstrates a composite panel optimisation based on industrial data and skill tools (damage tolerance, reparability, stability). It exposes a complete methodology providing a valid solution that does not violate any constraints (stress, stability and lay-up) and illustrates its flexibility.

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