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# OPTIMIZATION OF COMPOSITES WITH REPEATING SUB-LAMINATES

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## ABSTRACT

Composite material offers unmatched design and manufacturing flexibility. The increased complexity also presents new challenges for engineering design and manufacturing. In recently years the authors have developed a comprehensive optimization process for composite laminate structures [1-3]. This process is implemented in the commercial software OptiStruct and has gained increasing usage in broad range of industries, including design of next generation airliners at major aerospace OEMs. The first phase of this process focuses on generating design concept consists of thickness and shape of plies of different fibre orientations. This is accomplished by a free-size optimization formulation where thickness of each available fibre orientation is allowed to vary continuous. Manufacturable ply shapes are obtained through a semi-automatic processing of the result where ply boundaries are smoothed and smaller ply patches are merged or eliminated. Then the second design optimization phase continues with detailed sizing of ply patches of given ply shapes, typically including all design constraints some of which are ignored during the first concept phase. The final phase finishes the design details by optimizing stacking sequences of each individual base-thickness plies. Over the years increasing design manufacturing constraints were introduced to this design process, including ply thickness drop rate control [3] and more recently design of composite for ATL (automatic tape laying) manufacturing. An example of thickness blended aircraft wing cover design produced by this optimization process is shown in Fig.1. This paper addresses another aspect of composite laminate structures commonly used in aerospace industry – repeated sub-laminate structures. To accommodate this design requirement, we incorporate predefined sub-laminate properties from the very beginning of concept generation and carry it throughout the three-phase design process. Examples of airplane structures are given to demonstrate the effectiveness of this software implementation for engineering applications.

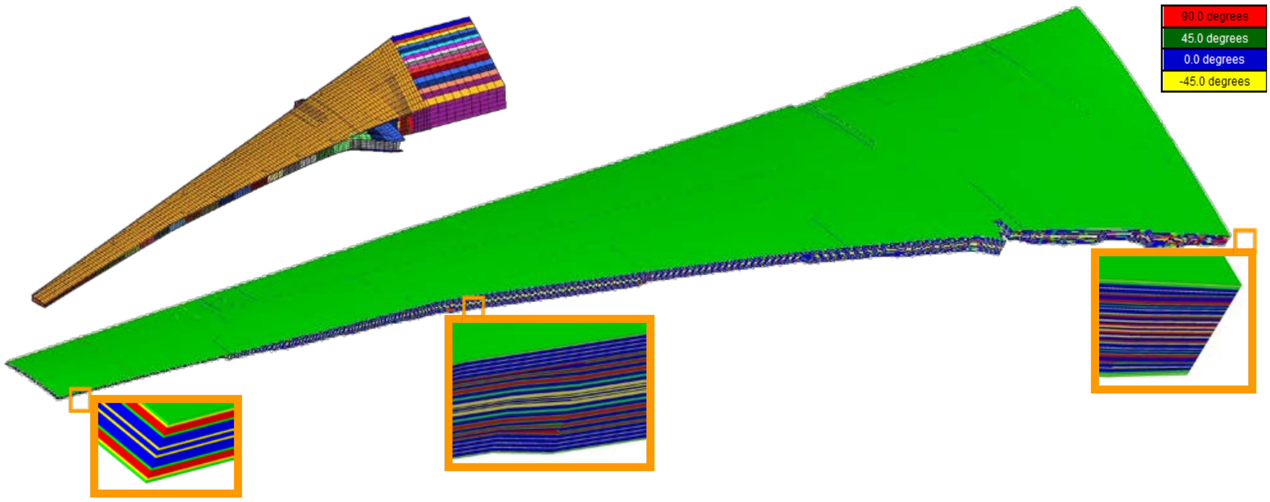


Fig.1 Top cover of composite wing of a wide-body airliner

## 1. Design formulation

The first design phase focuses on defining ply shapes of each available fibre orientation, modelled as 'super ply' during the first phase. This is achieved by Free-Size formulation where thickness of each super ply at each element is a variable. The optimization problem can be formulated as follows:

$$\begin{aligned} &\text{Minimize} \quad f(\boldsymbol{x}) \\ &\text{Subject to} \quad g_j(\boldsymbol{x}) - g_j^U \le 0, \quad j = 1,\ldots,M \\ &\qquad x_{ik}^L \le x_{ik} \le x_{ik}^U, \quad i = 1,\ldots,Np, k = 1,\ldots,NE \end{aligned} \tag{1}$$

Where *NE* is the number of elements and *Np* the number of super-plies; $x_{ik}$ is the thickness of the *i*-th super-ply of the *k*-th element. In addition, manufacturing constraints such as total thickness and ply percentage constraints are considered to addressing manufacturing and design rules:

$$\begin{aligned} &\text{Total thickness}: T_k^L \le \sum_{i=1}^{Np} x_{ik} \le T_k^U, \quad k = 1,\ldots,NE \\ &\text{Ply percentage}: P_j^L \le \frac{x_{jk}}{\sum_{i=1}^{Np} x_{ik}} \le P_j^U, \quad j = 1,\ldots,Np, k = 1,\ldots,NE \end{aligned} \tag{2}$$

Thickness blending is achieved by the following thickness slope constraint:

$$\text{Ply drop rate}: |x_{ij} - x_{ik}| \le \delta \cdot dist(j,k), \tag{3}$$

where $x_{ij}$ and $x_{ik}$ denote adjacent elements *j* and *k* of *i*-th super-ply, $\delta$ represents ply thickness dropping rate over one in-plane length unit, *dist*(*j*, *k*) the distance between element *j* and *k*. The aircraft wing example shown in Fig.1 applied ply drop rate constraint to achieve smooth blending thickness changes.

## 2. Design with ply pattern grouping

This design/manufacturing requirement initially came from a commercial aircraft OEM. Their design process required constant ply thickness for each zone intersect by stringers and ribs. Besides simplifying ply layout, the main reason is to accommodate legacy design criteria where each aforementioned zone is a panel unit for strength and stability evaluation. Therefore constant thickness within each panel is required for accurate calculation of its properties. This can be easily achieved by linking Free-Size variables in a zone as one independent variable. An illustrative example is shown in Fig. 2 where free-size results with and without zone-based pattern grouping are compared.

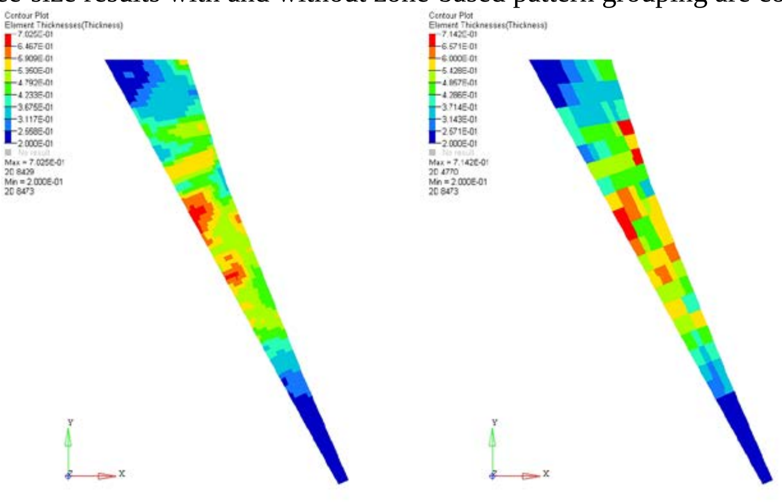


Figure 2. Thickness distribution of Free-Size results with and without pattern grouping

## 3. Repeat sub-laminate

Composite laminate built with repeating predefined sub-laminate can be of interest both from design and manufacturing perspectives. For design consideration, sub-laminate can be selected to reflect desired reserve stiffness and strength in none dominant orientations. As a result, the overall laminate will exhibit desired robustness against various load, material and manufacturing uncertainties. From manufacturing perspective, each sub-laminate can be pre-manufactured fabrics, possibly as pre-impregnated plies. This process can significantly increase manufacturing efficiency. A composite laminate build-up using sub-laminates is illustrated in Fig.3. For a sub-laminate which has distance d to the middle plane of the whole laminates, the in-plane properties [*A*], bending properties [*D*] and coupling properties [*B*] can be calculated as follows:

$$[A]=[A]^{'}$$
$$[B]=[B]^{'}+d[A]^{'}$$
$$[D]=[D]^{'}+2d[B]^{'}+d^{2}[A]^{'}$$

where

$$[A]^{'}=\int_{\frac{-t}{2}}^{\frac{t}{2}}[Q]dz^{'}=\sum_{k=1}^{n}[Q]_{k}(z_{k}^{'}-z_{k-1}^{'})$$
$$[B]^{'}=\int_{\frac{-t}{2}}^{\frac{t}{2}}[Q]z^{'}dz^{'}=\frac{1}{2}\sum_{k=1}^{n}[Q]_{k}(z_{k}^{'2}-z_{k-1}^{'2})$$
$$[D]^{'}=\int_{\frac{-t}{2}}^{\frac{t}{2}}[Q]z^{'2}dz^{'}=\frac{1}{3}\sum_{k=1}^{n}[Q]_{k}(z_{k}^{'3}-z_{k-1}^{'3})$$

For the entire repeat composite: the total ABD matrices are obtained by summing each sub-laminate, assuming there are *N* repeats:

$$[A]_{repeatlam}=\sum_{k=0}^{N-1}[A]=\sum_{k=0}^{N-1}N[A]^{'}$$
$$[B]_{repeatlam}=\sum_{k=0}^{N-1}[B]=\sum_{k=0}^{N-1}([B]^{'}+d_{k}[A]^{'})=N[B]^{'}$$
$$[D]_{repeatlam}=\sum_{k=0}^{N-1}[D]=\sum_{k=0}^{N-1}([D]^{'}+2d_{k}[B]^{'}+d_{k}^{2}[A]^{'})=N[D]^{'}+(\frac{N^{3}t^{2}-Nt^{2}}{12})[A]^{'}$$

The number of repeats *N* is the design variable during Free-Size stage. Once changes of *N* is interpreted into ply shapes after first optimization phase, the number of repeats for each ply of given layout can be further fine-tuned during 2nd optimization phase taking more detailed performance and manufacturing constraints into consideration. As usage of sub-laminates significantly decreases the impact of stacking sequence of ply groups, final stacking sequence may be carried out during post-processing for pure manufacturing considerations.

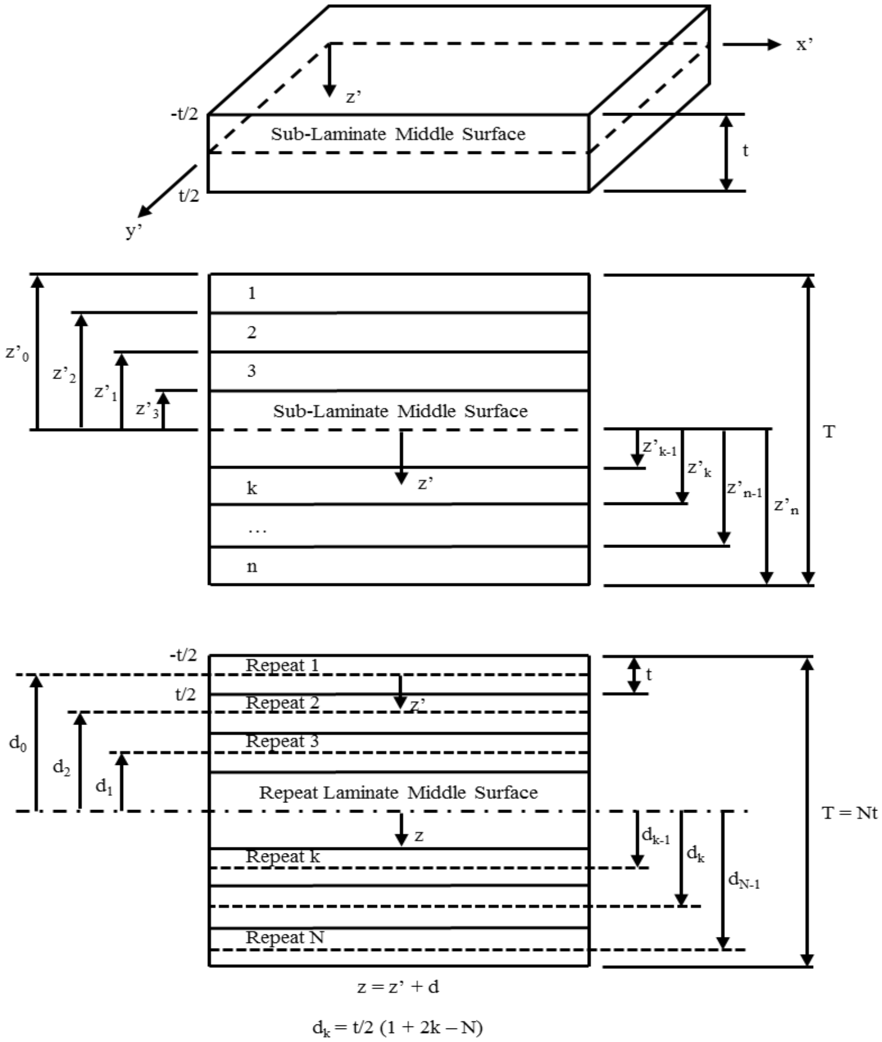


Figure 3. Composite laminate built with sub-laminates

## 4. References


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Design of composite structures can be viewed as a multi-faceted task, one which requires integration of issues related to composite mechanics, structural analysis, optimization, and manufacturing....Â  Mesquita, L., and Kamat, M.P., â€œOptimization of Stiffened Laminated Composite Plates with Frequency Constraints,â€ Engineering Optimization, 11, pp. 77â€“88, 1987.CrossRefGoogle Scholar. 8. Haftka, R.T., and Walsh, J.L., â€œStacking-Sequence Optimization for Buckling of Laminated Plates by Integer Programming,â€ AIAA Journal (in Press).Google Scholar. 9. Hajela, P., â€œGenetic Search-An Approach to the Nonconvex Optimization Problem,â€ AIAA Journal, 28, 7, pp. 1205â€“1210, 1990.CrossRefGoogle Scholar. After recalling the goal of optimization, the different laminates parameterizations will be presented with their limitations (the pros and the cons) in the frame of the optimal design of composite structures. The issues linked to the modeling of structures made of such materials and the problems solved in the literature will be reviewed.Â  For a sake of completion, the sensitivity analysis of the structural responses of composites with respect to those variables can be found in Mateus et al. (1991), Geier and Zimmerman (1994), and Dems (1996). 3.2.2 Parameterization with sub-laminates. The design parameters are no longer defined based on single unidirectional plies but instead on predefined sub-laminates. Each sub-laminate is itself made of several single unidirectional plies. 4 Stacking sequence optimization of laminated composites in pSeven. The above ideas and algorithms were implemented within the pSeven integration platform aimed to automate the solution of various engineering problems. In more details, pSeven provides an easy way to integrate various commercial and in-house developed tools into a united execution workflow, quantitatively describing multi-disciplinary properties of the studied design. A resulting model of the designed product could then be investigated with various mathematical methods ranging from Design of Experiments (DoE) studies to modern