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Optimal design of laminated composite structures with ply drops using stacking sequence tables

F.-X. Irisarri [a,*], A. Lasseigne [a,b], F.-H. Leroy [a], R. Le Riche [b,c]

[a] *Onera, The French Aerospace Lab, F-92322 Châtillon, France*
[b] *École Nationale Supérieure des Mines de Saint-Étienne, F-42023 Saint-Étienne, France*
[c] *CNRS LIMOS UMR 6158, France*

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A B S T R A C T

This article introduces the concept of stacking sequence table (SST) for the optimal design of laminated composite structures with ply drops. The SST describes the sequence of ply-drops ensuring the transition between a thick guide laminate and a thinner one. A blended design is represented by a SST combined with a thickness distribution over the regions of the structure. An evolutionary algorithm is specialized for *SST-based blending* optimization. Optimization of the sequence of ply-drops with the proposed algorithm enables satisfying design guidelines that could not have been considered in previous studies. An extensive set of design guidelines representative of the actual industrial requirements is introduced. The method is applied to an 18-panel benchmark problem from the literature with convincing results. In particular, the present results show that strength-related guidelines can be enforced without significantly penalizing the stiffness behavior and consequently the mass of the structure.

1. Introduction

Over the last decade, design and manufacturing of large scale one-shot structures using straight-fiber laminated composite materials have attracted increasing attention from structural designers. The mass of such structures can be minimized by progressively reducing the thickness away from the load introduction zones while allowing for oriented laminates to obtain locally optimized design. Detailed design of large composite structure is usually based on the subdivision of the global problem into local panel design problems. The subdivision results from higher design levels and is not meant to be called into question at lower design levels. Stiffness variations between panels are obtained by modifying the ply orientations and by adding or terminating plies. Continuity of the plies has to be preserved to obtain one-shot manufacturable structures and avoid stacking sequence mismatch between adjacent panels. The ply-drops form taper sections between adjacent panels. Ply-drops cause out-of-plane stress concentrations in tapers that can initiate in-plane matrix cracking and delamination.

In their literature survey on tapered composite structures, He et al. [1] bring out two major categories of studies. The first category aims at understanding the damage mechanisms at ply-drop locations and study the propagation of delamination in the structure. The second category aims at identifying and investigating the influent parameters on the strength of the taper section and propose design guidelines to reduce damage initiation at ply-drops. Since then a third category of related studies has developed that deals with the optimal design of composite structures with ply-drops. Review about the topic can be found in [2]. Designing laminated structures with ply-drops is commonly referred to as blending. There are few if any links between laminate blending optimization and the first two categories of studies. In particular, no design guidelines for the taper sections are considered in the optimization. Thus, there is no guarantee for the optimized designs that damages initiated at ply-drops could not propagate and lead to failure under the design loads. The present work intends to bridge the gap and introduce a complete set of relevant design guidelines into the optimization.

Industrial design guidelines for composite structures with ply-drops are summarized in Section 2. Section 3 provides background on blending and introduces the concept of stacking sequence tables (SSTs). Next, an evolutionary algorithm (EA) is specialized for SST-blending optimization in Section 4. Finally, the results obtained for an 18-panel benchmark from the literature are compared and discussed in Section 5.

2. Design guidelines

Laminate design starts by selecting the set of ply angles relevant to a given application. Due to manufacturing constraints, the allowed ply orientations are reduced to a discrete set of angles such

* Corresponding author. Tel.: +33 146734520; fax: +33 146734142.
E-mail address: francois-xavier.irisarri@onera.fr (F.-X. Irisarri).

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as {0^o, $\pm15^o$, $\pm30^o$, $\pm45^o$, $\pm60^o$, $\pm75^o$, 90^o}. Once the angles are selected, the total number of plies and proportion of each orientation in the laminate are set and a stacking sequence is chosen. Additionally, when designing structures comprising several zones of different thicknesses, thickness variations are obtained by dropping plies at specific locations. For both laminate stacking sequence design and ply-drop design, numerous guidelines apply, based on industry past experience from test and analysis. A more detailed discussion about design guidelines and their justification is provided in [3,4].

Six *laminate design guidelines* are considered as a basis for the design of the stacking sequences of most composite structures in aerospace industry.

1. *Symmetry*. Whenever possible, stacking sequences should be symmetric about the mid-plane.
2. *Balance*. Whenever possible, stacking sequences should be balanced, with the same number of $+\theta^o$ and $-\theta^o$ plies ($\theta \neq 0$ and $\theta \neq 90$).
3. *Contiguity*. No more than a given number of plies of the same orientation should be stacked together. The limit is set here to two plies.
4. *Disorientation*. The difference between the orientations of two consecutive plies should not exceed 45^o.
5. 10%-*rule*. A minimum of 10% of plies in each of the 0^o, $\pm45^o$ and 90^o directions is required. Here, to allow for other ply orientations, this rule is transposed in terms of a minimal in-plane stiffness requirement in all directions, as proposed by Abdalla et al. [5].
6. *Damtol*. No 0^o-ply should be placed on the lower and upper surfaces of the laminate.
   Symmetry and balance guidelines aim at avoiding respectively shear-extension and membrane-bending coupled behaviors. The other rules are beneficial to the strength of the structure. They aim at avoiding matrix dominated behaviors (10%-rule) and possible strength problem due to unwanted failure modes such as free-edge delamination (disorientation) or propagation of transverse matrix cracking (contiguity). With primary load carrying plies shielded from the exposed surface of the laminates (damtol), the effect on strength of exterior scratches or surface ply delamination is reduced.
   The *ply-drop design guidelines* aim on the one hand at avoiding delamination at ply-drop location and, on the other hand, at obtaining ply layouts that can actually be manufactured.
7. *Covering*. Covering plies on the lower and upper surfaces of the laminate should not be dropped.
8. *Maximum taper slope*. The taper angle should not exceed 7^o, i.e. the minimal stagger distance (the length of the increment of thickness) is about eight times the thickness of the dropped plies.
9. *Max-stopping*. No more than two plies should be stopped at the same increment of thickness.
10. *Internal continuity*. A continuous ply should be kept every three consecutive dropped plies.
11. *Ply-drop alternation*. As far as possible, ply-drops should be located alternately close and far from the mid-surface of the laminate.
12. *Taper guidelines*. All laminates in the taper section should respect to the maximum possible extend the laminate design guidelines.
    The schematic of a 4 ply-drop transition zone is shown in Fig. 1.
    All the above guidelines are local in the sense that they apply to the design of each individual panel of the structure, or each ply-drop. However, the design of a variable-thickness composite structure also has to fulfill two *global requirements*.
13. *Continuity*. This requirement aims at ensuring structural integrity and manufacturability of the structure. All plies from the thinner panel must cover the whole structure. Ply orientation mismatches between adjacent panels are not allowed, i.e. cutting plies between two panels to change their orientations is not allowed.
14. Δn-*rule*. The second requirement specifies a maximum number of ply-drops Δn between adjacent zones. Indeed, constraining the thickness variation between adjacent zones can help to smooth the load distribution over the structure and avoid high stress concentrations at dropped plies, especially interlaminar stresses.

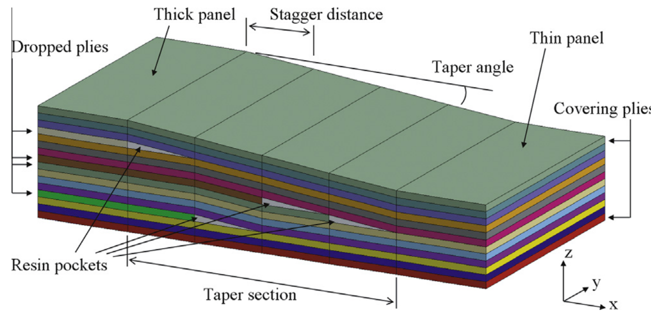

Fig. 1. Schematic of a taper section with four internal ply-drops.

3. Blending of laminates and stacking sequence tables

3.1. Blending definitions

The continuity requirement is commonly referred to as the blending constraint in the composite optimization literature. The term *blending* was first introduced by Kristinsdottir et al. in 2001 [6]. In their work, each ply emanates from a key region and may cover any number of adjacent regions. Once a ply is dropped, it is not allowed to be added back in the structure. The authors named this way of consistently dropping plies from the most loaded region the *greater-than-or-equal-to* blending rule. The method leads to highly constrained problems with many variables. Liu and Haftka [7] investigated the use of inequality constraints to enforce stacking sequence continuity, thus obtaining trade-offs between structural continuity and mass. Much smaller weight penalty for perfectly blended solutions were obtained by Soremekun et al. [8] using an approach based on sublaminates.

The most successful definition up to now originates from Adams et al. [9] in which the authors introduce the concept of *guide-based blending*. A guiding stack is defined from which all laminates in the structure are obtained by deleting contiguous series of plies. In case of *inner blending*, the innermost plies are dropped whereas in case of *outer blending*, the outermost plies are dropped. The main asset of the method is that blending is enforced without adding any constraint into the optimization problem while adding only one variable per region of the structure, representing the number of plies dropped from the guide. However contiguity of the deletions narrows the design space (see [10,11]).

Another worth mentioning approach is the *patch concept* proposed by Zehnder and Ermanni [12] and further used and developed in [13,14]. In this approach, a patch is a layer of arbitrary shape that can be positioned anywhere over the structure. At any