Multiscale composite optimization with design guidelines

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Abstract: Composites show two distinctive features that affect the way in which they are optimized. Firstly, manufacturing strongly interacts with structural performance. Secondly, composites can be described at different scales. This article summarizes contributions that address both features. It is shown how design guidelines can be accounted for in laminate blended design through stacking sequence tables and specialized evolutionary algorithms. It is also explained how the optimization can be made more efficient by simultaneously working at the ply and laminate levels.

Keywords: laminate, blending, design guidelines, stacking sequence table, evolutionary optimization

1. Introduction

Laminated composite materials are increasingly used for modern aeronautical structures. In parallel, optimization methods for composite structures have received growing attention from composite engineers and researchers. A review on the topic can be found in [1,2]. With composites, manufacturing constraints should be considered during the optimization as they interact with structural performance [19]. However, lay-up manufacturing and strength constraints remain a challenge to satisfy during design. They are the main topic of this article.

Sections 2 to 5 of this paper are dedicated to the design large one-shot composite panels, taking into account design guidelines. Detailed design of a 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. The mass of the structure can be minimized by tailoring the thickness and lay-ups of each panel to the local load distribution. For straight-fibre laminates, thickness variations between panels are achieved 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 design of laminated structures with ply-drops is commonly referred to as blending. The work presented here is detailed in [3]. A method for laminate blending optimization is proposed, which is able to handle a rich set of design guidelines aimed at preventing unwanted coupled behaviours and damage mechanisms too complex to be captured by the model.

Composites are architectured materials that can be optimized at various scales. This feature is exploited in Section 6, for single laminate, to create faster evolutionary algorithms.

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 as {0°, ±15°, ±30°, ±45°, ±60°, ±75°, 90°}. 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 [4,5].

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. Stacking sequences have to be symmetric about the mid-plane.
2. Balance. Stacking sequences have to be balanced, with the same number of +θ° and –θ° plies (with θ different from 0 and 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°.
5. 10%-rule. A minimum of 10% of plies in each of the 0°, ±45° and 90° 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.* [6].
6. Damtol. No 0°-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 behaviours. The other rules are beneficial to the strength of the structure. They aim at avoiding matrix dominated behaviours (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. The schematic of a 4 ply-drop transition zone is shown in Figure 1.

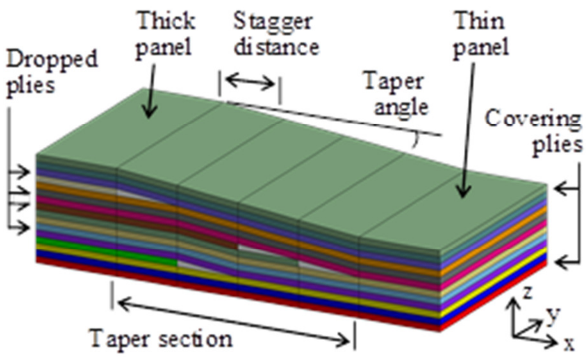

Figure 1: Schematic of a 4 ply-drop transition zone.

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°, i.e. the minimal stagger distance is about eight times the thickness of the dropped plies.
9. Max-stopping. No more than two plies should be stopped at the same location.
10. Internal continuity. A continuous ply should be kept every three consecutive dropped plies.
11. Ply-drop alternation. 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.

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 fulfil 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. Δ*n*-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.

3. Blending of laminates and stacking sequence tables

2.2 Laminate blending

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 [7]. 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 et al. [8] 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.* [9] using an approach based on sublaminates.

The most successful definition up to now originates from Adams *et al.* [10] 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 since the position and order of the ply-drops cannot be optimized.

Another worth mentioning approach is the patch concept proposed by Zehnder and Ermanni [11] and further used and developed in [12,13]. In this approach, a patch is a layer of arbitrary shape that can be positioned anywhere over the structure. At any point of the structure, the stacking sequence is defined by the order and orientations of the patches. The patch concept is very appealing in the sense that the parameterization directly derives from the physical composition of laminated structures and does not narrow the design space. However the large number of degrees of freedom offered by the method makes engineering problems difficult to solve. Additionally, optimization of the shape and size of the constitutive regions of the structure is out of the scope of this paper.

2.2 Stacking sequence tables

In all the studies mentioned above, the set of design guidelines handled is restricted to the continuity, symmetry and balance guidelines. In this paper, we introduce the Stacking Sequence Table (SST) as a convenient tool to handle the full set of guidelines listed in Section 2. The SST originates in composite panels manufacturing practice from aeronautical industry. A SST describes a unique laminate for each number of plies between a lower bound n_{min} and an upper bound n_{max}. Figure 2 shows a SST ranging from a 12-ply laminate (n_{min} = 12) to a 16-ply laminate (n_{max} = 16). Plies are added one by one from the thinner laminate to the thicker one (in the right-hand column of the table). Thus, plies from the thinner laminate spread over the whole structure and ensure its continuity. For a given structure and a given distribution of numbers of plies over its constitutive regions, the laminate associated to each region can be read in the SST based on its number of plies. The laminates in the transition zone between two regions of different thicknesses are also described in the SST. The SST describes general thickness distributions, not only monotonously varying thicknesses: once the thickness of a region is set, the associated laminate is read from the SST which can therefore be read in any order.

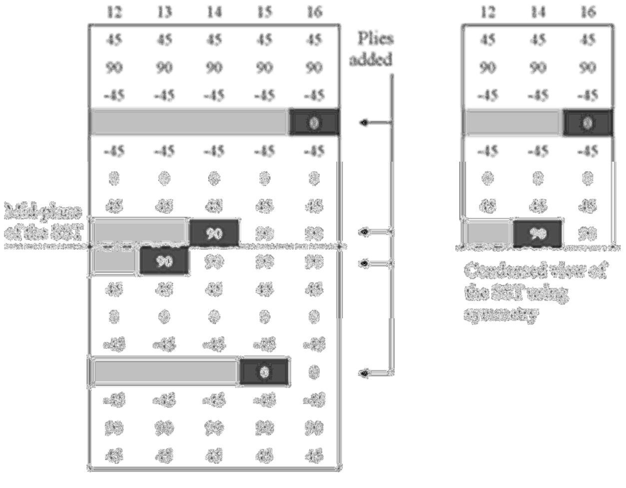

Figure 2. SST with four internal ply drops (n_{min} = 12 and n_{max} =16). Full view and condensed view using symmetry. The numbers of plies of the laminates are indicated over the corresponding columns.

Compared to the guide-based blending as proposed in [10], the SST contains additional information consisting in the order of the ply-drops. Thus, the notion of SST encompasses the classical guide-based blending by providing a more detailed description of the layout of the plies over the structure and affording more freedom to define which plies to drop. Additionally, satisfaction of the ply-drop design guidelines can be assessed based on the SST.

4. Evolutionary optimization of stacking sequence tables

In the following, an Evolutionary Algorithm (EA) is specialized for laminate blending optimization using SST. Although EAs may not be the most efficient discrete optimization methods compared to branch and bound or other exact algorithms, they provide, through encoding and variation operator definitions, means of accounting for complex constraints such as the design guidelines. A specialized definition of the encoding and variation operators will ensure that constraints are satisfied at SST creation; therefore it can be considered that they proceed by projection of the designs onto the feasible space. Reviews about the use of EA for stacking sequence optimization of composite structures can be found in [1,2,14]. The Pareto multiobjective EA used in the present study is based on previous work by Irisarri *et al.* [15,16]. A generic EA is made of the following steps:

1. Creation of an initial set of designs
2. Sample: create λ new designs either by applying variation operators to the set of μ good designs (crossover, mutation) or by sampling a density *p*.
3. Evaluate the performance of the λ new designs
4. Update: keep the μ best designs out of the λ or update the density *p*.
5. If maximum number of analyses not exceeded, go to 2, else stop.

4.1. Encoding

The algorithm is specialized for combined thickness and laminate blending optimization, using an encoding based on stacking sequence tables (SST). Applying the metaphorical terminology of EAs to the laminate blending problem, the phenotype is a decoded design which consists of the set of r laminates corresponding to the r regions of the panel. Additionally, the complete phenotype must also define the ply-drops between zones of different thickness. The phenotype of a blended solution can be conveniently represented by a SST and the distribution of the numbers of plies over the structure. The thickness of the ply, the number r of regions of the panel, their numbering and connectivity are fixed parameters of the problem.

The genotype encodes the solution in vectors called chromosomes. In this work, a three-chromosome genotype is proposed. Two chromosomes are devoted to the SST and one to the thickness distribution over the structure.

i. Chromosome SST_{lam} represents the stacking sequence of the thickest laminate of the SST. SST_{lam} is an integer vector of length n_{max}.

ii. Chromosome SST_{ins} contains the rank of insertion of the plies from the thinner laminate to the thicker one. SST_{ins} is an integer vector of length n_{max}. The first ply introduced is given rank 1, the second ply rank 2 and so on. Plies from the thinner laminate are given rank 0. Thus, the vector contains n_{min} zero values.

iii. Chromosome N_{str} represents the distribution of the numbers of plies over the structure. It is an integer vector of length r.

Table 1 shows the genotype of the 2-region structure described in Figure 1. The symmetry guideline allows encoding half of the SST only.

N_{str}	[16 12]
SST_{lam}	[45 90 -45 0 -45 0 45 90]
SST_{ins}	[0 0 0 2 0 0 0 1]

Table 1. Genotype of a 2-region structure (n_{min} = 12 and n_{max} = 16).

4.2. Design guidelines handling

The evolutionary algorithm is implemented so that, at each of its step, the encoded solutions, i.e. the chromosomes, satisfy the design guidelines. The operations of the EA that affect the design chromosomes are the initialization of the population and the variation operators. These operators are all devised according to the same general principle. The following steps are repeated, sometimes in a recurrent way, until the initialization or variation is complete.

a) *Selection of a subset of the optimization variables*. For example, it can be a one angle component of SST_{lam}, or more generally it can be any subset of any chromosomes.

b) *Enumeration of guidelines compatible values*. Enumerate and store all possible values of the optimization variables within this subset that satisfy the purpose of the operator and all the guidelines.

c) *Random choice*. Choose at random, with uniform probability, one of the feasible subset of optimization variables values and assign it to the chromosome.

4.3. Evolutionary operations for stacking sequence tables

Creation of a feasible SST starts from the thinner laminate. The procedure for the creation of laminates satisfying the laminate design guidelines has already been published in [16] and follows the general principle presented in Section 4.2. Once the thinner laminate is chosen plies are added one-by-one until the maximum number of plies in the SST n_{max} is reached, thus building the SST column by column from the thinner laminate to the thicker one (see Figure 3).

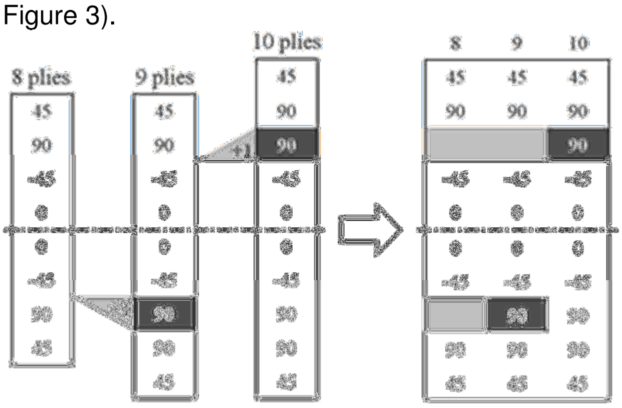

Figure 3. Creation of a SST.

Adding plies one by one in the SST necessarily generates unsymmetrical and/or unbalanced laminates. If a 0°-ply or a 90°-ply is added to a symmetrical laminate, the next ply added reestablishes symmetry. If θ is different from 0 and 90, symmetry is restored first, then balance. In the first case, a cycle of length 2 is formed, in the second case, a cycle of length 4. Such cycles are called *SB-cycles* and used to modify SSTs in the following.

The mutation operator for SSTs modifies chromosome SST_{lam} or SST_{ins} with equal probability. The mutation operator for SST_{lam} modifies the orientation of a pair of ± θ°-plies or a couple of plies of orientation 0° or 90°. The new orientation is randomly chosen in a set of feasible orientations that depends on the orientations of the neighboring plies in the SST and the contiguity and disorientation guidelines. Figure 4 shows an example of mutation of chromosome SST_{lam} and the corresponding variation of the SST.

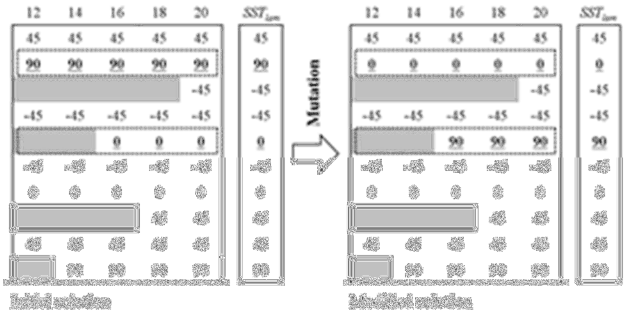

Figure 4. Mutation of chromosome SST_{lam} and corresponding variation of the SST.

The mutation operator for chromosome SST_{ins} permutes the order of insertion of two SB-cycles. The permutation is illustrated in Figure 5. In the figure, cycles are identified with Roman numerals. Cycles I and II are permuted to generate a new solution. The corresponding variation of SST_{ins} is shown in the figure.

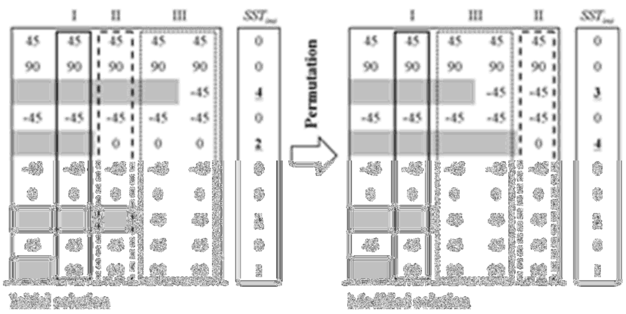

Figure 5. Permutation within chromosome SST_{ins} and corresponding variation of the SST. SB-cycles are numbered with Roman numerals. Cycles II and III are permuted.

The crossover operator exchanges same-length balanced sublaminates between the thinner laminates of the parent solutions. The respective position of the two sublaminates within chromosome SST_{lam} can differ. Offspring SSTs are scanned from the thinner laminate to the thicker one for violation of the contiguity and disorientation guidelines. Unfeasible SSTs are cut before their first unfeasible column. The remaining columns are regenerated using the creation procedure of SSTs.

4.4. Evolutionary operations for thickness distribution

The only guideline applying to chromosome N_{str} is the Δn-rule which defines a maximum difference Δn between the number of plies of contiguous zones. Contiguity between zones is defined by a r-by-r array of connectivity which is a fixed parameter of the problem. Feasible instances of N_{str} are created by random generation of uniform distributions of number of plies over the structure.

The mutation operator modifies the number of plies associated to a region *i*. The new number of plies in region *i* is randomly selected in the set of admissible values which are defined by n_{min}, n_{max}, Δn and the number of plies of the regions connected to region *i*.

A 2-point crossover is used to exchange sequences of genes between the two parent chromosomes. A preliminary scan is performed to identify which genes can be exchanged with respect to the Δn-rule. Contiguous sequences formed of these genes are exchanged only.

The proposed encoding and the corresponding operator maintain a complete separation between the thickness distribution and the SST. Nevertheless, the notion of SB-cycles calls for a comment. Allowing the number of plies per panel to take any value in the range n_{min} to n_{max} would result in designs composed of unsymmetrical or unbalanced laminates or both. Forcing the optimizer to drop full cycles restricts the search to designs composed of symmetrical and balanced panels only.

5. Results

The test problem consists of 18 panels in a horseshoe configuration (r = 18), as shown in Figure 6. The problem was proposed by Soremekun et al. [9] and subsequently examined in [10,17,18]. The dimensions of the panels and the local loadings are given in the figure. The loads are assumed to be fixed. All panels are assumed to be simply supported on their four edges. n_{min} is set to 14 and n_{max} is set to 48. A Graphite/Epoxy IM7/8552 material is used with E_1 = 141 GPa (20.5 Msi), E_2 = 9.03 GPa (1.31 Msi), G_{12} = 4.27. GPa (0.62 Msi) and ν_{12} = 0.32. Ply thickness is 0.191 mm (0.0075 inch). Ply orientations are restricted to 0°, ±15°, ±30°, ±45°, ±60°, ±75° and 90°. The objective is to find a fully blended design that minimizes the mass of the structure without individual panel failure under buckling. The minimal buckling factor over the individual panels is called Reserve Factor and noted RF in the following. Buckling analysis is performed using a closed form solution, as in [9].

In the present work, the problem is stated as follows: minimize the total mass of the structure and maximize the reserve factor under the constraint that no individual panel fails under buckling (RF > 1). The termination criterion corresponds to a maximum number of generations. It should be pointed out that, although load redistribution is not taken into account here, the proposed method presents no intrinsic limitation in that regard. FE modelling is required to assess load redistributions in complex structures what raises the problem of the calculation costs. A two-step design method, as in [18], or response surface methods, as in [16], may be needed to circumvent the difficulty.

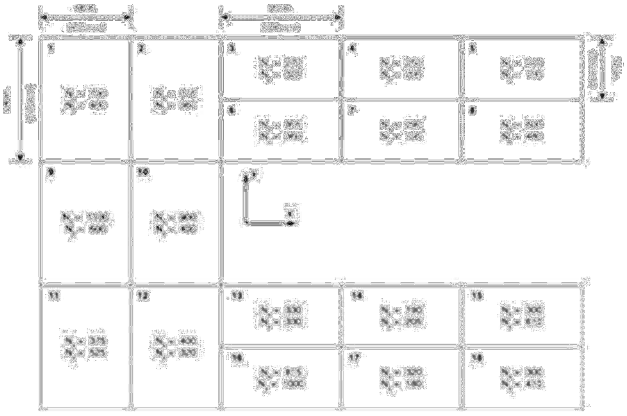

Figure 6. 18-panel test problem [9], all loads in lbf/in (×175.1 for N/m).

Figure 7 presents the solutions of a single optimization run. Feasible and unfeasible solutions are identified in the figure, depending on whether they satisfy or not the two constraints (10%-rule and RF > 1). Convergence to the lightest solution is examined in Figure 8 over 5 runs. After 2000 generations, all 5 curves are less than 30 kg (about 1.05 × m0). After 4000 generations, the lightest feasible solutions are reached for 4 runs over 5. All curves are less than 29.3 kg (about 1.023 × m0). Analysis of the whole non-dominated fronts shows that, for each run, the front after 2000 generations is already very close to the final non-dominated set. The EA achieves very good exploration of the decision space during the first part of the search. During the next generations, it is mostly the density and the distribution of the solutions along the non-dominated front that are improved.

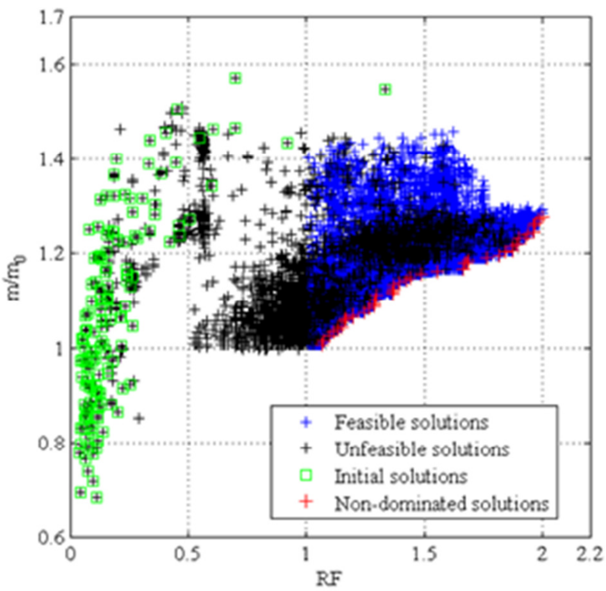

Figure 7. Results of the optimization of the 18-panel test problem, all guidelines are enforced. Solutions obtained during a single optimization run.

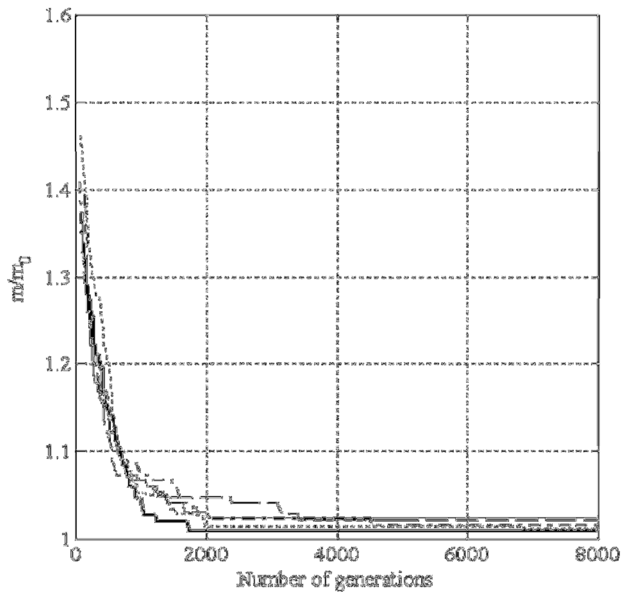

Figure 8. Convergence of the EA over 5 runs.

The lightest feasible solution obtained compares very well with the best designs published by other authors. Seresta *et al.* [17] report an innerly blended design composed of symmetrical and balanced laminates with a mass of 28.82 kg and a 1% buckling margin. The lightest solution found in the present work (solution 1) weights 28.85 kg and presents a buckling margin of 6.8%. The performances of the solution are detailed in Table 2.

Panel	Solution 1		Seresta *et al.* [17]	
	n	Margin (%)	*n*	Margin (%)
1	34 (0)	17.2	34	13.1
2	30 (2)	15.9	28	2.3
3	22 (0)	36.4	22	12.5
4	18 (-2)	13.3	20	23.1
5	18 (2)	59.3	16	3.7
6	22 (0)	22.6	22	1.1
7	18 (-2)	9.8	20	19.2
8	26 (0)	31.9	26	12.3
9	38 (0)	6.9	38	1.0
10	38 (2)	25.6	36	10.1
11	30 (0)	10.0	30	30.6
12	30 (2)	27.1	28	1.9
13	22 (0)	28.3	22	5.8
14	18 (-2)	20.2	20	40.6
15	26 (0)	27.8	26	8.9
16	30 (0)	6.8	30	11.4
17	18 (-2)	11.3	20	20.9
18	22 (-4)	11.2	26	51.1

Table 2. Result comparison for symmetrical and balanced laminates. Differences of numbers of plies per panels are marked between brackets.

The corresponding genotype is given in Table 3. The present results show that strength-related guidelines can be enforced without significantly penalizing the stiffness behaviour and consequently the mass of the structure.

Solution 1. Mass: 28.85 kg. RF = 1.068 (panel 16)	
N_{str}	[34 30 22 18 18 22 18 26 38 38 30 30 22 18 26 30 18 22]
SST_{lam}	[45 45 60 30 45 30 30 45 90 -45 -30 -45 90 90 -45 -45 90 -60 -30 -45 0 -30 0 45]
SST_{ins}	[0 5 2 12 0 10 13 7 0 8 11 6 0 15 3 0 16 1 14 0 17 9 0 4]

Table 3. Genotype of Solution 1. Chromosome N_{str} is repaired for symmetry and balance. Performances of the solution are computed based on repaired chromosome N_{str}.

6. Taking advantage of the composite various scales: the DDOA algorithm

Optimizing at the ply level, as was done in this article so far, leads to large design spaces (12^{nmax} possibilities just for SST_{lam}) where the EA needs many evaluations to find good solutions. Such a cost will not be acceptable if composites are analyzed with a numerical simulator (e.g., nonlinear finite elements, as opposed to closed form solutions). In an attempt to make EAs for composite design more efficient, it has been proposed in [20] to optimize simultaneously at two scales, the ply and the laminate levels. The associated EA was named Double Distribution Optimization Algorithm (DDOA). A new explanation of DDOA in terms of conditional probabilities is now given. DDOA has been developed for one laminate. It is an EA where the crossover and mutation operators are replaced by a probability density function, $p(\theta)$, which is in turns sampled and updated. $p(\theta)$ can be interpreted as a probability of presence of an optimum design.

In this sense, DDOA is an instance of Estimation of Density Algorithms. The simplest EDA is the Univariate Marginal Distribution Algorithm (UMDA) [21] in which the density does not account for couplings between variables, i.e., $p(\theta) = \prod_{i=1}^{n} p_i(\theta_i)$. In the update step of UMDA, $p_i(\theta_i)$ is calculated as the frequency of ply orientation θ_i at the *i*-th ply among selected high performance laminates. In the sample step of UMDA, $p_i(\theta_i)$ is the probability that the new generated laminates have orientation θ_i at the *i*-th ply. The advantage of UMDA is that the density is simple (it has $n \times A$ scalar frequencies to set where A is the number of possible ply orientations) and therefore easy to learn from few laminate evaluations. But the UMDA does not describe coupled ply effects which may not allow the algorithm to describe where are the optimum designs eventhough all the necessary information is available. This phenomenon is sketched in two dimensions in Figure **9** where the UMDA density is not the highest at the optimum.

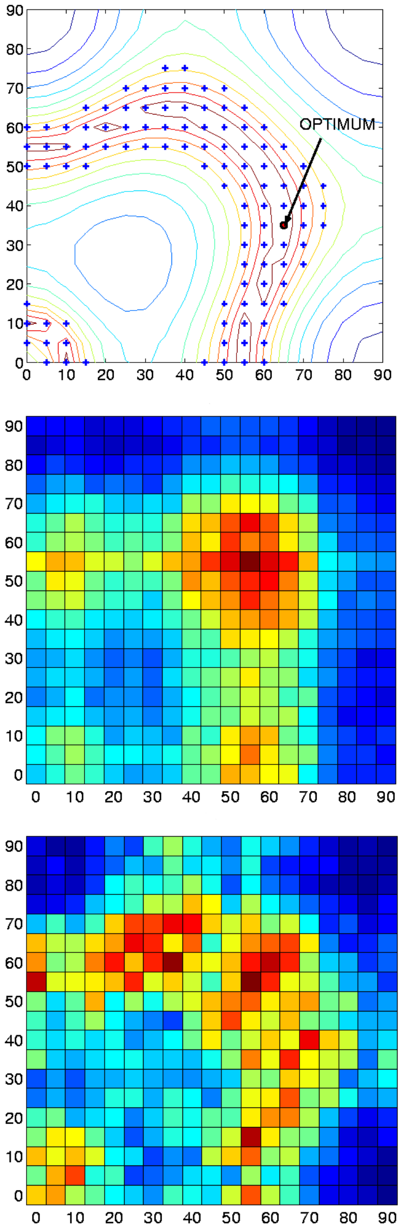

Figure 9. (top) contour lines of a max first eigen frequency problem with constraints on Poisson's ratio; (middle) density learned by a UMDA algorithm; (bottom) density learned by DDOA.

DDOA [20] takes advantage of auxiliary variables defined at a larger scale, the lamination parameters, v. The lamination parameters are laminate stiffnesses normalized by material constants. A complete definition of lamination parameters can be found in [22]. For our purpose, suffice is to understand that *i)* lamination parameters relate to the orthotropic stiffness at the laminate scale and therefore account for some of the ply interactions. *ii)* They can be calculated from the stacking sequence at no computational cost but the reverse is not true:

ply orientations are not a function of lamination parameters (many or no sequences may be associated to a particular vector of v's). In other terms, a laminate is only fully specified when characterized at the lowest scale, that of ply orientations here. *iii)* The number of v's per laminate is 2 (membrane behavior) or 4 (when accounting for the flexural behavior) whichever the number of plies n of the laminate.

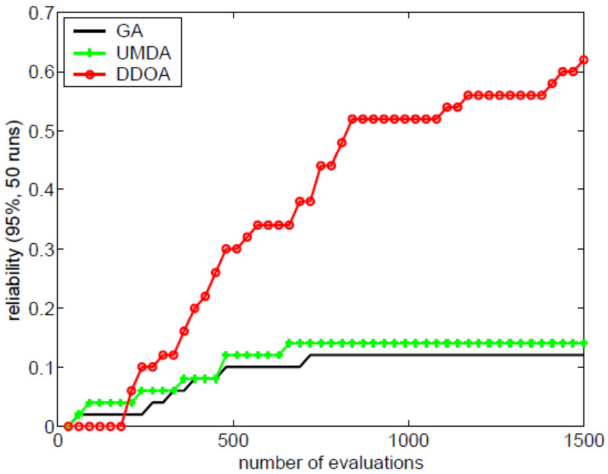

Figure 10. Reliability of the optimization vs. number of analyses for the UMDA, EA (here a Generic Algorithm) and the DDOA algorithms, strength maximization problem, from [20].

DDOA uses two probability density functions p_Θ and p_V in the space of ply angles and lamination parameters, respectively. $p_\Theta(\theta)$ is simply the UMDA density described earlier. $p_V(v)$ is modeled as a sum of Gaussian kernels centered on the v's of the μ selected designs. The kernels have the same bandwidth which is calculated by maximum likelihood. Note that there is no extra computational cost associated to the learning of p_V because it is tuned from the same laminate evaluations as p_θ. DDOA creates new laminates by repeatedly sampling from the two densities, $p_\theta(\theta)$ and $p_V(V)$ in a particular way: firstly, new target lamination parameters v^{targ} are obtained by sampling from $p_V(V)$; secondly a large number, ν, of stacking sequences is sampled from $p_\theta(\theta)$, $\theta^i, i = 1, \nu$. The laminate created by DDOA and kept for evaluation is the one whose stacking sequence has associated lamination parameters the closest to the target lamination parameters,

$$\theta^{new} = \arg\min_{i=1,\nu} dist(v(\theta^i), v^{targ})$$

This procedure is in fact a Monte Carlo sampling of the random variable $(\Theta \,|v(\Theta) = V)$ which is DDOA's way to couple the independent random variables Θ and V defined at two scales.

As can be seen in Figure 9, DDOA can describe coupled densities. Experimentally, many tests were done in [20] that illustrate how DDOA can converge faster than UMDA or even a classical genetic algorithm. Figure 10 illustrates the performance of DDOA on a strength maximization problem with $n = 12$ independent stack of plies. The performance of the algorithm is measured in terms of the reliability, which is the probability of locating the optimum design out of 50 independent runs.

7. Conclusions

This article summarizes contributions that address two distinctive features of composite laminates that affect the way in which they are optimized.

Firstly, manufacturing strongly interacts with structural performance. Therefore, lay-up manufacturing and strength constraints have to be taken into account during design. This paper presents the concept of stacking sequence table (SST) for the 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 position and order of the ply-drops enables satisfying design guidelines that were discarded in previous studies. An extensive set of design guidelines representative of actual industrial requirements has been introduced. The laminate design guidelines aim at preventing unwanted coupled behaviours, matrix dominated behaviours or premature failure modes in the panels. The ply-drop design guidelines aim at avoiding delamination at ply-drop location and obtaining ply layouts that can actually be manufactured. The global requirements aim at ensuring ply continuity and smooth load redistribution over the structure. Accounting for the guidelines in the optimization is possible by devising specific evolutionary operators. A clear distinction is made between guidelines and other constraints such as buckling. Guidelines are enforced by construction of the solutions whereas constraints are incorporated to the objectives of the optimization through penalty functions. The method is applied to a benchmark problem from the literature with convincing results.

Secondly, the paper shows how the optimization can be made more efficient by simultaneously working at the ply and laminate levels. The Double Distribution Optimization Algorithm (DDOA) is an advanced EA devised to guide the optimization by combining probability distributions at both scales.

8. References

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