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Towards a streamlined stacking sequence optimisation methodology for blended composite aircraft structures

Georgios Ntourmas[a,b†] *Ender Özcan*[c] *Dimitrios Chronopoulos*[a] *Florian Glock*[b] *Fernaß Daoud*[b]
[a] *Composites Research Group, The University of Nottingham*
NG7 2RD, United Kingdom
[b] *Stress Methods and Optimisation, Airbus Defence and Space GmbH*
85077 Manching, Germany
[c] *Automated Scheduling, Optimisation and Planning Research Group, The University of Nottingham*
NG7 2RD, United Kingdom
georgios.ntourmas@nottingham.ac.uk · ender.ozcan@nottingham.ac.uk ·
dimitrios.chronopoulos@nottingham.ac.uk · florian.glock@airbus.com · fernass.daoud@airbus.com
[†] Corresponding author

Abstract

In order to fully exploit the benefits provided by using composite materials in large scale aerospace structures, more efficient detailed design optimisation techniques need to be developed. In the present work, the optimisation procedure is split up in one gradient-based step that yields an optimal thickness and stiffness distribution which is then matched by a following discrete optimisation step. The output structure meets prescribed design and manufacturing rules commonly applied in composite design, through the implementation of a novel Mixed Integer Linear Programming formulation of the problem. The results indicate the need for more efficient discretisation techniques.

1. Introduction

Modern aeronautical structures are increasingly made out of fibre reinforced plastics, because these offer reduced weight and enhanced mechanical characteristics. Aside from this, composites are generally anisotropic materials, providing the engineer with increased design freedom compared to classic metallic materials. However, the problem that arises is that with an increased design freedom the complexity of sizing the structure in detail also increases.

Detailed sizing of aerospace composite structures concerns the optimisation of the layering characteristics and thickness of large scale structures, which are discretised in so-called zones or patches. During the optimisation process, a large set of constraints must be taken into account. First of all, so-called design rules regulating the stacking characteristics of a zone in the material are applied. In addition to optimising in the direction parallel to the thickness of the structure, there is also the need to optimise in the planar view of the structure. More specifically, different zones across the structure have different optimal stiffness distributions and hence stacking sequence characteristics. In order to ensure structural integrity and manufacturability, these different zones need to be smoothly blended into a design which obeys specific rules known as blending or manufacturing constraints. A description of the design and blending rules can be found in the work of Irisarri *et al.* [16] or Bermell-Garcia *et al.*[4] Finally, the structure needs to fulfill a large set of physical constraints which might include amongst others, strength, buckling, aeroelasticity and damage tolerance constraints.

The problem of composite stacking sequence optimisation has been studied thoroughly by many researchers over the last decades. A bibliographic review of different approaches on stacking sequence optimisation has been performed by Ghiasi *et al.*[11,12] Genetic algorithms have been extensively used to tackle the problem of stacking sequence optimisation[21,25,30] because they are especially suited to handle problems with discrete design variables and allow for a rather straightforward implementation. Other metaheuristics such as ant colony optimisation[3], particle swarm optimisation[7], simulated annealing[8] and hybrid algorithms[17] have also been used. However, one-shot optimisation approaches using only metaheuristics or other deterministic optimisation algorithms are bound to fail for industry applications, since the number of optimisation cycles grows exponentially for an increased number of design variables, while the computational cost of each optimisation cycle is also considerably high.

Gradient-based optimisation algorithms enable faster convergence than deterministic algorithms, but are suited for continuous design variables. Although stacking sequence optimisation is a highly discrete problem, gradient-based methods have been applied[6,10,20,23,28,29] by using penalty functions in order to drive the design variables to their feasible discrete values. Overall, the applicability of the methodologies is likely limited by the size of the problem and can only be used as an initial sizing step as further processing is needed in order to derive design and blending compliant structures.

In an attempt to combine the benefits and eliminate the drawbacks of both gradient and deterministic algorithms a two step optimisation process has been employed by several researchers. During the first step, a thickness optimisation[26,34,35] or thickness and stiffness optimisation using lamination parameters[14,24,32] is performed using a gradient-based algorithm. Within this step, the physical constraints of the problem need to be taken into account, as the inclusion of those also makes each optimisation cycle computationally expensive. The result of this step is an optimal, continuous distribution of thickness and stiffness characteristics which needs to be discretised in order to be sensible from a manufacturing point of view. An optimal discretised result can be used as a target by the second step of the optimisation process which is usually a deterministic algorithm[5,15,18,22] which can handle design and manufacturing rules more efficiently.

2. Methodology

The optimisation process followed in the current work is split up in two different optimisation steps as shown in Figure 1. First, a thickness optimisation is performed using the Airbus in-house Multidisciplinary Optimisation platform called Lagrange[26]. The structure is manually discretised into patches, which represent areas that will be considered as individual laminates during the optimisation. Eventually, each patch in the structure is assigned a predefined generic stack containing one of the 4 standard ply orientations $\{0^o, 90^o, 45^o, -45^o\}$ commonly used in industrial applications. The thickness of each individual layer is used as a design variable in a weight minimisation problem under strength and buckling constraints (see Figure 2). Next, the lamination parameters are calculated for the optimal layer thicknesses of the prescribed generic stack. In order to mitigate the reduction of design freedom arising from using a generic stack, a sufficiently large number of layers needs to be defined within the stack. The optimal thicknesses calculated in the first optimisation step have to be discretised to a thickness value which corresponds to an integer number of layers, given that the thickness of the composite tape used in manufacturing is known. Currently, this discretisation is a simple rounding operation.

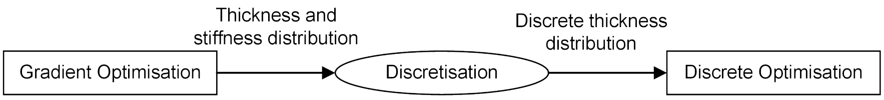


Figure 1: Two different optimisation steps are applied during the process.

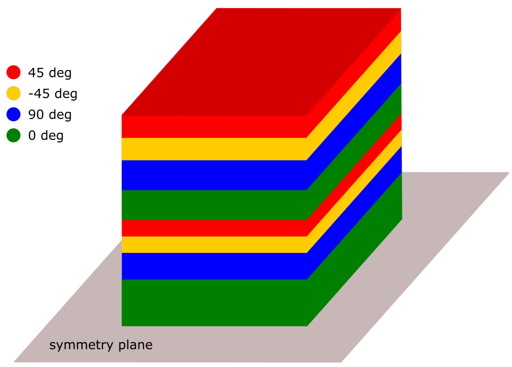


Figure 2: An indicative generic stack of 16 plies results in 6 design variables, due to linking constraints between design variables which define symmetry and laminate balance.

The second step of the optimisation process aims to match the prescribed discretised thicknesses and optimal lamination parameters, while enforcing all design and blending constraints so that the resulting structural design can be readily manufactured. This discrete optimisation step is formulated as a Mixed Integer Linear Programming (MILP) problem and solved by using the commercial optimiser Gurobi[13].

2.1 Lamination parameters

Lamination parameters were introduced by Tsai and Pagano[31]. They are used to decouple the stacking-sequence-dependent part from the material-dependent part of a laminate stiffness matrix. In the general case of an anisotropic laminate, 12 lamination parameters and 5 material parameters fully define the stiffness matrix. For the case of a symmetric laminate, the bending extension coupling stiffness matrix **B** is zero and the extensional stiffness **A** and bending stiffness **D** matrices are formulated as:

$$\begin{bmatrix} A_{11} \\ A_{22} \\ A_{12} \\ A_{66} \\ A_{16} \\ A_{26} \end{bmatrix} = h \begin{bmatrix} 1 & \xi_1^A & \xi_3^A & 0 & 0 \\ 1 & -\xi_1^A & \xi_3^A & 0 & 0 \\ 0 & 0 & -\xi_3^A & 1 & 0 \\ 0 & 0 & -\xi_3^A & 0 & 1 \\ 0 & \xi_2^A/2 & \xi_4^A & 0 & 0 \\ 0 & \xi_2^A/2 & -\xi_4^A & 0 & 0 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{bmatrix} \tag{2.1}$$

$$\begin{bmatrix} D_{11} \\ D_{22} \\ D_{12} \\ D_{66} \\ D_{16} \\ D_{26} \end{bmatrix} = \frac{h^3}{12} \begin{bmatrix} 1 & \xi_1^D & \xi_3^D & 0 & 0 \\ 1 & -\xi_1^D & \xi_3^D & 0 & 0 \\ 0 & 0 & -\xi_3^D & 1 & 0 \\ 0 & 0 & -\xi_3^D & 0 & 1 \\ 0 & \xi_2^D/2 & \xi_4^D & 0 & 0 \\ 0 & \xi_2^D/2 & -\xi_4^D & 0 & 0 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{bmatrix} \tag{2.2}$$

In the above equations, **U** denotes the material constants and h the thickness of the laminate. The lamination parameters are defined as:

$$\xi^A_{[1,2,3,4]} = \frac{1}{h}\int_{-\frac{z_i}{2}}^{\frac{z_i}{2}} [\cos(2\theta), \sin(2\theta), \cos(4\theta), \sin(4\theta)]dz \tag{2.3}$$

$$\xi^D_{[1,2,3,4]} = \frac{12}{h^3}\int_{-\frac{z_i}{2}}^{\frac{z_i}{2}} [\cos(2\theta), \sin(2\theta), \cos(4\theta), \sin(4\theta)]z^2dz \tag{2.4}$$

where $-\frac{z_i}{2}$ and $\frac{z_i}{2}$ stand for the distance of the bottom and top layer of the i^{th} ply with respect to the midplane of the laminate.

2.2 Mixed Integer Linear Programming formulation

The current work includes the calculation of stacking sequences which comply with the specified design and blending rules. A list of these rules, using the naming conventions used by Irisarri *et al.* [16], is given in Table 1. Rule 4 implies grouping 45^o and -45^o layers within the laminate to minimize coupling effects. This rule is used in this work instead of the disorientation rule since these two rules are contradictory and cannot be applied simultaneously. Rules that are implicitly implemented are fulfilled, not by using constraints, but through appropriate choice of the design variables of the problem.

The input for the stacking sequence calculation is a simple geometric definition of the patches, together with the optimal number of layers and lamination parameters for each patch. The problem is formulated using a linear objective function, linear constraints and a combination of binary and integer variables. It is therefore categorized as a MILP problem. A formulation of the design rules in such a way has been performed in the literature[2,33]. To the best of the authors' knowledge, there has not been a formulation of the blending rules before in a similar way with the exception of Kang and Blom[19], who nonetheless treated the blending rules in the context of compliance with pre-computed laminates, which is not the case for the present work.

2.2.1 Formulation of design and blending rules

In order to formulate the blending and stacking sequence optimisation, various design variables need to be introduced. Each family of design variables, i.e. x, r, u, t, ξ, contains many individual members. The number of members for each family depends on the usage of the design variable and different indexes are used to distinguish between individual members of each family of design variables. Index $i \in \{1, 2, ..., I_j\}$ is used to

Table 1: Current status of the implementation of the design and blending rules. Naming conventions used by Irisarri *et al.* [16]

#	Rule description	Implemented in gradient optimisation	Implemented in discrete optimisation
1	Symmetry	Implicitly	Yes
2	Balance	Implicitly	Yes
3	Contiguity	Implicitly	Yes
4	Group 45/-45	Implicitly	Yes
5	10%-rule	Yes	No
6	Damtol	Implicitly	Yes
7	Covering	Implicitly	Yes
8	Maximum taper slope	Yes	No
9	Max-stopping	No	No
10	Internal continuity	No	No
11	Ply-drop alternation	No	No
12	Continuity	No	Yes
13	Δn-rule	Yes	No

Table 2: Summary of indexes used to denote the various design variables

Name	Description
i	Layer
j	Patch
h	Interface between neighboring patches
p	Blending possibility between plies of neighboring patches
θ	Fiber orientation
k	Lamination parameter

denote the exact layer in a specific patch $j \in \{1, 2, ..., J\}$. The range of i is not constant for all patches j, but rather takes a maximum value of I_j according to the patch of interest. Index $h \in \{1, 2, ..., H\}$ accounts for all interfaces between neighboring patches and index $p \in \{1, 2, ..., P_h\}$ takes into account the different blending combinations between neighboring patches. A more detailed explanation of these two indexes will be presented in the following paragraphs. Index θ denotes the different available fiber orientations with $\theta \in \{1 \rightarrow 0^o, 2 \rightarrow 90^o, 3 \rightarrow 45^0, 4 \rightarrow -45^o\}$ and $k \in \{1, 2, 3, 4\}$ distinguishes between the lamination parameter which is of interest. A summary of the design variables employed in the discrete optimisation is given in Table 2.

The objective function of the optimisation problem minimises the deviation from the optimal set of lamination parameters and is mathematically formulated as:

$$min|\sum_{j=1}^{J}[\,\xi_{kj}^{D} - (\xi_{kj}^{D})_{optimal}\,]| \qquad \forall k \tag{2.5}$$

where $\xi_{kj}^{D} \in [-1, 1]$ are the lamination parameters for a specific stack, whereas, $(\xi_{kj}^{D})_{optimal}$ are the constant optimal parameters passed over from the gradient-based optimisation. In the most general case, lamination parameters ξ_{k}^{B} may also be matched in a similar fashion, but this does not apply for symmetric laminates currently examined. The objective function is not linear in its current form because of the absolute values, therefore, a simple linearisation needs to be performed.

The constraints defining the problem are the following: Firstly, the matching for ξ^A is defined. Since the stacking sequence does not influence ξ^A, which only depends on the number of layers per fiber orientation in the patch, a preprocessing step is carried out in order to calculate the number of layers for each orientation. This preprocessing step is as simple as solving a system of four linear equations for the case where the standard set of 0,90,45,-45 fiber orientations is used. If more fiber orientations are of interest, the value of ξ^A could also be incorporated in the objective function of the problem, in a similar manner to that of ξ^D. For the case of four standard fiber orientations, the following system of equations can be easily derived from Equations 2.3-2.4:

$$\nu_{j1} + \nu_{j2} + \nu_{j3} + \nu_{j4} = n_j \qquad \forall j \tag{2.6}$$

$$\nu_{j1} - \nu_{j2} = n_j \xi^A_{1j} \qquad \forall j \tag{2.7}$$

$$\nu_{j3} - \nu_{j4} = n_j \xi^A_{2j} \qquad \forall j \tag{2.8}$$

$$\nu_{j1} + \nu_{j2} - \nu_{j3} - \nu_{j4} = n_j \xi^A_{3j} \qquad \forall j \tag{2.9}$$

In the above equations n_j is the total number of layers for each patch and $\nu_{j\theta}$ is the number of layers per orientation per patch.

To make the formulation of the problem possible, the binary design variables $x_{ij\theta} \in \{0, 1\}$ defining the orientation of a specific layer within a certain patch are introduced. More specifically, every layer consists of θ design variables, each one representing whether the corresponding fiber orientation is used or not. The ξ^A matching constraint can now be formulated as:

$$\sum_{i=1}^{I_j} x_{ij\theta} = \nu_{j\theta} \qquad \forall j, \theta \tag{2.10}$$

Each layer may only have one orientation, therefore, the following feasibility constraint needs to be defined.

$$\sum_{\theta=1}^{4} x_{ij\theta} = 1 \qquad \forall i, j \tag{2.11}$$

The contiguity constraint limits the number of consecutive layers having the same fiber orientation to a maximum of N. In a mathematical formulation, this is expressed as:

$$x_{ij\theta} + x_{(i+1)j\theta} + \ldots + x_{(i+N)j\theta} \leq N \qquad \forall i \in \{1, 2, ..., I_j - N\}, j, \theta \tag{2.12}$$

In many cases laminates are designed to be symmetric. Whenever symmetry is required, the following constraints must be incorporated in the optimisation model.

$$x_{ij\theta} = x_{(I_j - i+1)j\theta} \qquad \forall i \in \{1, 2, ..., I_j/2\}, j, \theta \tag{2.13}$$

The damage tolerance rule requires the outermost two plies being equal to 45^o and -45^o accordingly. These same two layers have to be continuous over all patches according to the covering rule. The next set of constraints fulfills both requirements.

$$x_{1j3} = 1 \qquad \forall j \tag{2.14}$$

$$x_{2j4} = 1 \qquad \forall j \tag{2.15}$$

Finally, the $45^o/-45^o$ grouping rule is formulated as:

$$x_{ij3} \leq x_{ij4} \qquad \forall i \in \{1, 2, ..., I_j/2\}, j \tag{2.16}$$

The formal definition of lamination parameters has already been presented in the previous section. Before moving on to the definition of the remaining constraints, it is worth formulating the lamination parameter values in a way that serves the specific approach to the problem.

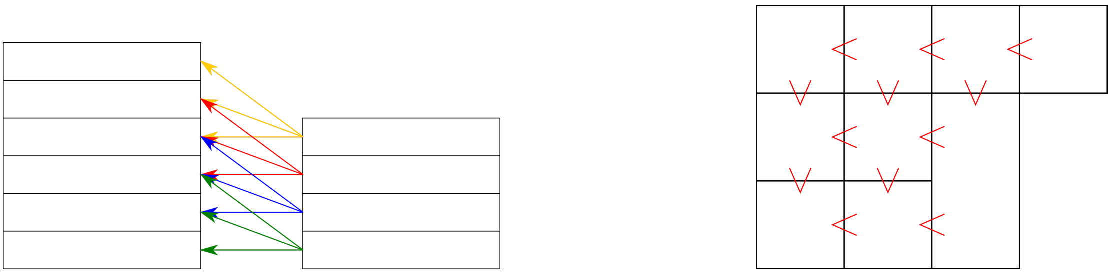
$$\xi^D_{kj} = \sum_{i}^{I_j} \sum_{\theta}^{4} s_{k\theta} a^D_{ij} x_{ij\theta} \qquad \forall j \tag{2.17}$$

Coefficients $s_{k\theta}$ take into consideration the influence of the trigonometric terms depending on which θ design variable is used out of $x_{ij\theta}$. Additionally, coefficients a^D_{ij} depend on the position of the ply within the laminate and can be pre-calculated during the setup of the problem.

The continuity between neighboring patches also needs to be formulated as a set of linear constraints. A new family of design variables $r_{ih\theta p} \in \{0, 1\}$ is defined. It contains information on whether the orientation of a specific ply within a patch can be blended with one of the p possible neighboring plies. The number of possibilities p depends on the interface h examined and can easily be determined during the setup of the optimisation problem. A representation of the different plies that could blend between two patches is given in Figure 3a. More specifically, for any of the interfaces h, the maximum number of of possibilities can be calculated as:

$$P_h = |n_{j_1} - n_{j_2}| + 1 \tag{2.18}$$

In the above equation, patches j_1 and j_2 denote the two patches which constitute an interface h, with j_1 being the thickest of the two, in case there is a difference in thickness between them. The number of interfaces H is easily calculated prior to setting up the optimisation problem based on the arrangement of the patches. In Figure 3b, an example of the interfaces between a specific patch geometry is given.



(a) Knowing the number of ply drops between two neighboring patches, the different blending possibilities can be determined for each ply.

(b) The interfaces between patches are marked with red ticks for the given patch geometry.

Figure 3: Illustrative examples showing usage of indexes p and h

In order for the design variables $r_{ih\theta p}$ to contain the necessary information, they are defined as $r_{ih\theta p} = x_{(i+p-1)j_1\theta} x_{ij_2\theta}$. In this way, if the examined fiber orientations of two different plies belonging to neighboring patches are both equal to 1, then blending could exist between them. Because the definition of $r_{ih\theta p}$ is non-linear, a standard linearisation needs to be performed. This linearisation of the product of two binary variables is defined by the following inequalities[9]:

$$r_{ih\theta p} \leq x_{(i+p-1)j_1\theta} \qquad \forall i, h, \theta, p \tag{2.19}$$

$$r_{ih\theta p} \leq x_{ij_2\theta} \qquad \forall i, h, \theta, p \tag{2.20}$$

$$r_{ih\theta p} \geq x_{(i+p-1)j_1\theta} + x_{ij_2\theta} - 1 \qquad \forall i, h, \theta, p \tag{2.21}$$

Another family of design variables $u_{ihp} \in \{0, 1\}$ is defined in order to accumulate the information contained in $r_{ih\theta p}$ for all possible orientations of a specific ply. Essentially, u_{ihp} indicates whether two plies belonging in different patches have the same orientation and is defined as:

$$u_{ihp} = \sum_{\theta}^{4} r_{ih\theta p} \qquad \forall i, h, p \tag{2.22}$$

By definition, ${}_{p}u_i^h$ is also a binary design variable, as each layer can only have one 'active' fiber orientation.

Finally, a last family of design variables $t_{ihp} \in \{0, 1\}$ is introduced. The number and structure of members for t_{ihp} follows the same pattern as u_{ihp} and is used to regulate and keep track of which layers blend with each other. A new constraint is defined as:

$$u_{ihp} \geq t_{ihp} \qquad \forall i, h, p \tag{2.23}$$

This constraint ensures that when the decision variable ${}_{p}t_i^h$ is switched on, the material orientations take such values so that blending occurs. This constraint alone is not enough to ensure manufacturable composite patches. Three further sets of constraints need to be defined to ensure the blending between individual layers is achieved in a meaningful manner.

$$\sum_{p}^{P_h} t_{(i-p+1)h(P_h-p+1)} \leq 1 \qquad \forall i, h \tag{2.24}$$

$$\sum_{p}^{P_h} t_{ihp} = 1 \forall i, h \tag{2.25}$$

$$\sum_{p}^{P_h} t_{(i-1)hp}(P_h - p + 1) \leq \sum_{p}^{P_h} t_{ihp}(P_h - p + 1) \forall i, h \tag{2.26}$$

The presented set of equations is implemented using the Python interface of Gurobi.

2.2.2 Guiding patch

The approach presented in the previous section, solves the stacking and blending optimisation problem as a whole. What might be useful in common practice is solving the stacking sequence optimisation problem of a single patch without considering any of the blending constraints and then using this as the guiding patch for the rest of the design. Regarding the solution procedure, a guiding patch would require fixing the corresponding design variables to a specified value. The concept of guiding patches has been introduced by Adams *et al.*[1] and used by many others including Ijsselmuiden *et al.* and Seresta *et al.*[15,27]

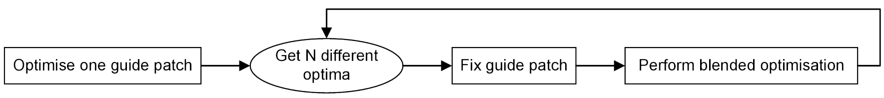


Figure 4: Simple flow chart of the optimisation procedure when using guiding patches.

For a specific set of provided lamination parameters, there might be many or no exact stacking sequence matches. For lamination parameters which have been calculated by a continuous gradient-based optimisation, the latter is most likely to be the case, however, a large number of different stacking sequences might result in lamination parameters whose values approach the specified target very closely. The bounds for treating a calculated stacking sequence as a possible guide must be chosen. This directly affects the computational expenses of the entire optimisation process.

Another choice that needs to be made concerns the patch to be treated as a guide for the structure. Choosing the thickest patch as the guide, results in a larger number of optimal matches for the same user-defined optimality bounds, but the design space that is left to be explored is significantly shrinked resulting in smaller computational expenses per inner optimisation cycle. On the other hand, choosing one of the thinner patches as a guide for the design would result in a smaller number of potential guides, but a larger computational time per inner optimisation cycle as the design space is not shrinked to the same extent.

3. Results

Initially, some results from a demonstrator case are presented in order to assess the discrete optimisation methodology presented. As a next step, a subset of an industrial problem is presented in order to demonstrate the complete optimisation process.

3.1 Ideal demonstrator case

The presented discrete optimisation approach is able to produce fully blended composite designs that meet all of the specified design and blending rules. An illustrative result produced for a methodology demonstrator problem is shown in Figure 5. In order to set up this demonstrator problem, a stacking which fulfills all prescribed design and blending rules is manually defined and the corresponding lamination parameters which are used as target values during the optimisation are calculated for each individual patch. The geometry of the problem used is shown in 6.

In Table 3, some data concerning the runtimes of the discrete optimisation for different problem instances are presented. The runtime of the optimisation grows too big for large problem instances. Runtimes marked with a star correspond to a stop due to reaching maximum optimisation time and the ones without

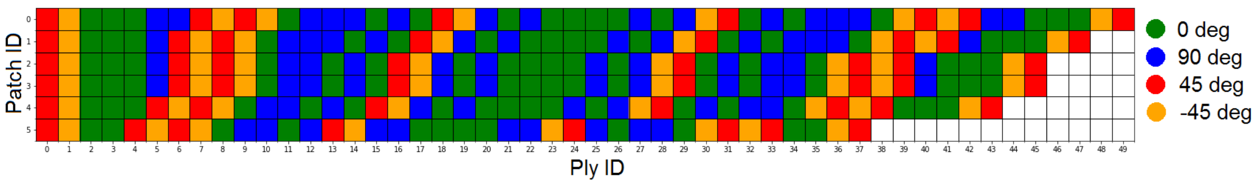


Figure 5: Resulting stacking sequence for the demonstrator problem.

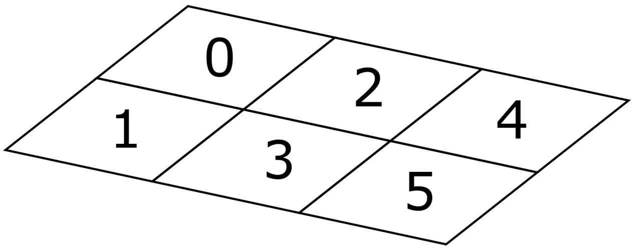


Figure 6: Patch geometry definition for result shown in 5.

a star correspond to the optimiser finding the optimal solution which for this case is known *a priori* and has an objective value equal to zero. All runs have been performed on a personal computer which uses CPU Intel Core i5-8250U @1.60GHz (4 cores, 8 threads) and a RAM of 8 GB. By default all threads are used by Gurobi.

Additionally, in Table 4 the final MILP problem size in terms of the number of design variables and constraints is presented. The final MILP size does not directly correspond to the numbers one would theoretically calculate given the problem definition, because Gurobi (as other commercial solvers), applies pre-solve algorithms that usually slightly reduce the size of the problem. It can be observed that the size grows significantly for large instances.

The runtime for finding an optimal solution can be drastically reduced when using the guiding patch concept. In Table 5, the same problem instance which is comprised of 6 patches and 50 plies in the thickest patch is optimised treating different patches as the guide ones. It is worth having a closer look at the choice and number of the different individual stacking sequences which are considered for the chosen guide patch. The number of guide designs which is shown in Table 5 is chosen arbitrarily from a pool of available stacking sequences which exactly match the provided target lamination parameters. This pool is generated by forcing the optimiser to find the N best solutions to the individual patch stacking sequence optimisation problem and not terminate when finding an optimal solution. Although this number N highly depends on the set of lamination parameters which is provided, some indicative results for lamination parameter sets which are known to be feasible are provided. In the case of a laminate having 100 plies, this number is larger than 200 000, the exact number not being determined due to the increased computational cost. For 50 plies, there are approximately 3 900 exact matches, while for 38 plies this number is 190. Once again, these results are not indicative for an arbitrary set of lamination parameters, but they do provide a rough estimation of how much the design space increases as the number of plies increase. It would seem more appropriate to use thinner patches as guides, since matching the stiffness characteristics of a thin patch is more difficult than matching those of a very thick laminate.

Table 3: Runtimes for different problem instances.

Instance	Num. of patches	Max num. of layers	Runtime (s)
1	6	30	5
2	2	50	45
3	3	50	74
4	4	50	164
5	6	50	675
6	2	100	13 560
7	4	100	18 000*

*Unconverged

Table 4: MILP problem size

Description			Discrete optimisation problem size		
Instance	Num. of patches	Max num. of layers	Rows	Columns	Non-zeros (%)
1	6	30	8 236	3 569	0.075
2	2	50	3 182	1 448	0.192
3	3	50	5 219	2 334	0.117
4	4	50	7 108	3 090	0.087
5	6	50	16 836	7 234	0.037
6	2	100	11 660	5 140	0.054
7	4	100	57 585	24 754	0.011

Table 5: Runtime comparison of a specific problem instance using different guiding patches.

6 patches, maximum 50 plies	
60 guides from thickest patch	588s
5 guides from thinnest patch	891s

3.2 OptiMALE aircraft subcase

In this section, the potential of the entire optimisation process is applied to OptiMALE, an industrial demonstrator of an aircraft drone. As seen in Figure 7, a subset of patches located at the upper skin of the aircraft's wing box are examined. In the first step of the gradient-based optimisation, the thickness of user defined generic plies is optimised. An adequate number of generic plies needs to be used in order to mitigate the reduced design freedom effect of prescribing the stacking of the generic plies. In this case, a total of 48 generic plies are defined for each patch i.e. $[(45, -45, 90, 0)_6]_s$. The size of the continuous problem for 10 patches and 90 examined load cases grows to 180 design variables, 161 280 constraints and 34 596 degrees of freedom. The discrete optimisation step converges after only 534s.

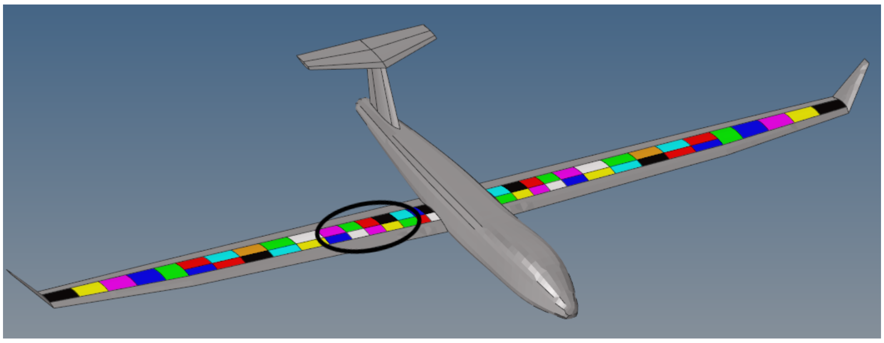
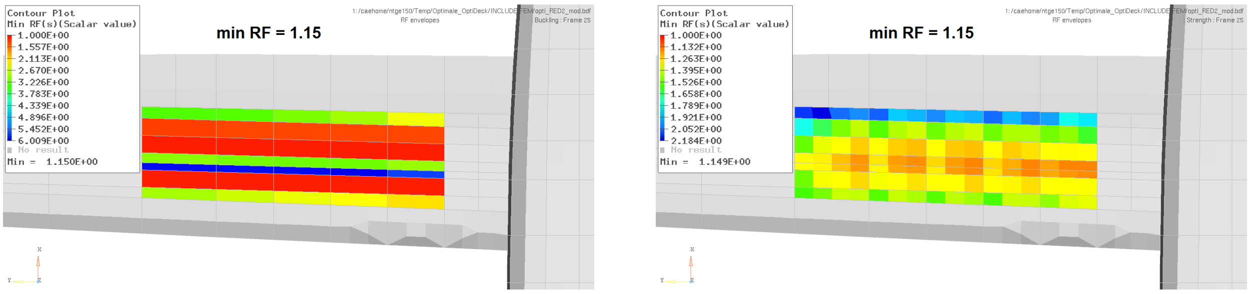


Figure 7: Subset of patches examined for the OptiMALE aircraft

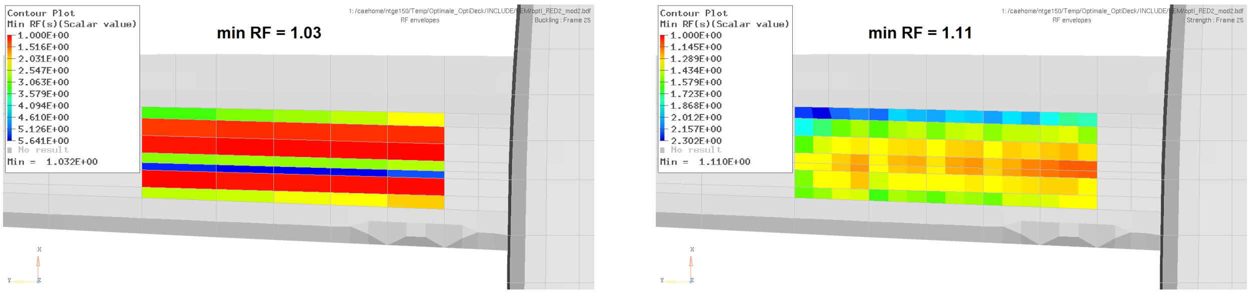
However, the lack of blended designs which closely match the target optimal stiffnesses for each individual patch, results in violation of the physical constraints of the structure i.e. strength and buckling. Therefore, there is a need to optimise for higher reserve factors during the gradient-based optimisation which, of course, increases the weight of the structure. In Figures 8-10, we see the reserve factors for strength and buckling for the optimised subset of patches. The reserve factor is defined as the ratio of the allowable stress over the applied stress. Therefore, reserve factors smaller than unity indicate a violation of the physical constraints. In Figure 8, the reserve factors calculated for the optimal thicknesses of the gradient-based optimisation are presented. Every patch has been pushed to the target reserve factor value of 1.15 which is used here to mitigate expected physical constraint mismatches. In 9, results are presented for a blended design produced by the discrete optimisation. In this case patch thicknesses have been rounded off and a small increase of 0.4% with respect to the weight of the continuous design is observed. Finally, in Figure 10 a round-up is performed for all patch thicknesses, resulting in a weight increase of 3.0% of the structure, with, as expected, higher reserve factors.

It is apparent that optimising for higher reserve factors and simply rounding the thicknesses for each patch individually is not the best remedy for obtaining manufacturable designs which still meet the physical constraints. In the future, either smarter discretisation techniques need to be implemented or the gradient-based optimisation needs to be performed in a way that smoother stiffness distributions are obtained allowing the discrete optimisation process to closely match these distributions.



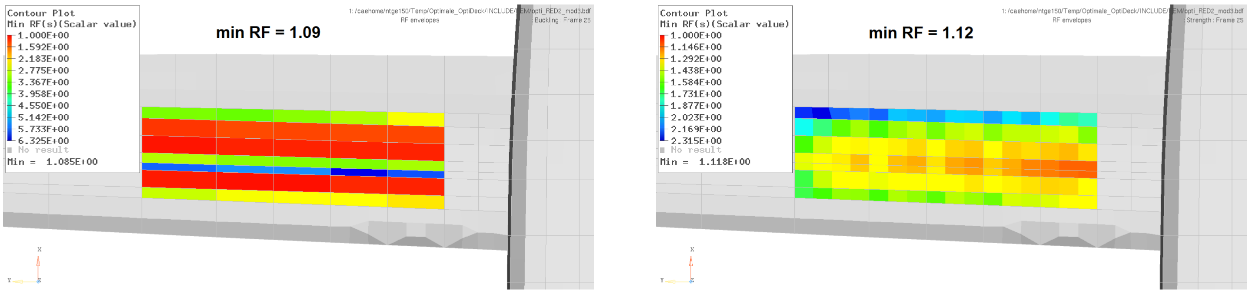
(a) Buckling (b) Strength

Figure 8: Reserve factors for the result of the gradient-based optimisation



(a) Buckling (b) Strength

Figure 9: Reserve factors for the result of the discrete optimisation having performed rounding-offs for the thickness of each patch.



(a) Buckling (b) Strength

Figure 10: Reserve factors for the result of the discrete optimisation having performed rounding-ups for the thickness of each patch.

4. Conclusion

A two step optimisation approach for the layering design of aerospace composite structures has been presented within the general framework of a multidisciplinary optimisation platform. A gradient-based continuous optimisation using generic stacks is used to find an optimal stiffness and thickness distribution which is then discretised and matched by a discrete optimisation carried out in the second step. A MILP formulation for the blending of composite structures has been demonstrated as part of the discrete step of the process, which results in structures complying with the prescribed design and blending rules while allowing for complete design freedom during the optimisation process. The computational expenses seem to be acceptable for industrial sized applications. Future work will focus on further enhancement of the capabilities of the current discrete optimisation step. Moreover, an efficient, automated feedback loop needs to be established in order to eliminate designs which are mis-compliant with respect to physical structural constraints.

5. Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 764650.

References

[1] David B. Adams, Layne T. Watson, Zafer Gürdal, and Christine M. Anderson-Cook. Genetic algorithm optimization and blending of composite laminates by locally reducing laminate thickness. *Advances in Engineering Software*, 35(1):35 – 43, 2004.

[2] G. Allaire and G. Delgado. Stacking sequence and shape optimization of laminated composite plates via a level-set method. *Journal of the Mechanics and Physics of Solids*, 97:168–196, 2016.

[3] F. Aymerich and M. Serra. Optimization of laminate stacking sequence for maximum buckling load using the ant colony optimization (aco) metaheuristic. *Composites Part A: Applied Science and Manufacturing*, 39(2):262–272, 2008.

[4] Pablo Bermell-Garcia, Wim J.C. Verhagen, Simon Astwood, Kiran Krishnamurthy, Jean Luc Johnson, Domingo Ruiz, Gary Scott, and Richard Curran. A framework for management of knowledge-based engineering applications as software services: Enabling personalization and codification. *Advanced Engineering Informatics*, 26(2):219 – 230, 2012.

[5] M. Bruyneel, S. Zein, and S. Grihon. A two-step optimization approach for the optimal design of composite structures, including geometric non-linear behavior, design rules and manufacturing constraints. In *4th Aircraft Structural Design Conference*, 2014.

[6] Michael Bruyneel. Sfp—a new parameterization based on shape functions for optimal material selection: application to conventional composite plies. *Structural and Multidisciplinary Optimization*, 43(1):17–27, Jan 2011.

[7] N. Chang, W. Wang, W. Yang, and J. Wang. Ply stacking sequence optimization of composite laminate by permutation discrete particle swarm optimization. *Structural and Multidisciplinary Optimization*, 41(2):179–187, 2010.

[8] Ozgur Erdal and Fazil O. Sonmez. Optimum design of composite laminates for maximum buckling load capacity using simulated annealing. *Composite Structures*, 71(1):45 – 52, 2005.

[9] Christodoulos A. Floudas. *Nonlinear and Mixed-Integer Optimization: Fundamental and Applications*. New York: Oxford University Press, 1995.

[10] T. Gao, W. Zhang, and P. Duysinx. A bi-value coding parameterization scheme for the discrete optimal orientation design of the composite laminate. *International Journal for Numerical Methods in Engineering*, 91(1):98–114, 2012.

[11] H. Ghiasi, K. Fayazbakhsh, D. Pasini, and L. Lessard. Optimum stacking sequence design of composite materials part ii: Variable stiffness design. *Composite Structures*, 93(1):1–13, 2010.

[12] H. Ghiasi, D. Pasini, and L. Lessard. Optimum stacking sequence design of composite materials part i: Constant stiffness design. *Composite Structures*, 90(1):1–11, 2009.

[13] LLC Gurobi Optimization. *Gurobi Optimizer Reference Manual*, 2018.

[14] J.E. Herencia, P.M. Weaver, and M.I. Friswell. Initial sizing optimisation of anisotropic composite panels with t-shaped stiffeners. *Thin-Walled Structures*, 46(4):399–412, 2008.

[15] S.T. IJsselmuiden, M.M. Abdalla, O. Seresta, and Z. Gürdal. Multi-step blended stacking sequence design of panel assemblies with buckling constraints. *Composites Part B: Engineering*, 40(4):329–336, 2009.

[16] F.-X. Irisarri, A. Lasseigne, F.-H. Leroy, and R. Le Riche. Optimal design of laminated composite structures with ply drops using stacking sequence tables. *Composite Structures*, 107:559–569, 2014.

[17] F. Javidrad, M. Nazari, and H.R. Javidrad. Optimum stacking sequence design of laminates using a hybrid pso-sa method. *Composite Structures*, 185:607–618, 2018.

[18] Z. Jing, X. Fan, and Q. Sun. Global shared-layer blending method for stacking sequence optimization design and blending of composite structures. *Composites Part B: Engineering*, 69:181–190, 2014.

[19] Laura Sumi Kang and Adriana Willempje Blom. Optimization of ply orientations for multi-layer composite parts, 2016.

[20] C.Y. Kiyono, E.C.N. Silva, and J.N. Reddy. A novel fiber optimization method based on normal distribution function with continuously varying fiber path. *Composite Structures*, 160:503 – 515, 2017.

[21] R. Le Riche and R.T. Haftka. Optimization of laminate stacking sequence for buckling load maximization by genetic algorithm. *AIAA Journal*, 31(5):951–956, 1993.

[22] D. Liu, V.V. Toropov, M. Zhou, D.C. Barton, and O.M. Querin. Optimization of blended composite wing panels using smeared stiffness technique and lamination parameters. 2010.

[23] E. Lund and J. Stegmann. On structural optimization of composite shell structures using a discrete constitutive parametrization. *Wind Energy*, 8(1):109–124, 2005.

[24] M. Miki and Y. Sugiyama. Optimum design of laminated composite plates using lamination parameters. *AIAA Journal*, 31(5):921–922, 1993.

[25] M. Montemurro, Y. Koutsawa, S. Belouettar, A. Vincenti, and P. Vannucci. Design of damping properties of hybrid laminates through a global optimisation strategy. *Composite Structures*, 94(11):3309–3320, 2012.

[26] G. Schuhmacher, F. Daoud, Ö. Petersson, and M. Wagner. Multidisciplinary airframe design optimisation. volume 1, pages 44–56, 2012.

[27] O. Seresta, Z. Gürdal, D.B. Adams, and L.T. Watson. Optimal design of composite wing structures with blended laminates. *Composites Part B: Engineering*, 38(4):469–480, 2007.

[28] Søren N. Sørensen and Erik Lund. Topology and thickness optimization of laminated composites including manufacturing constraints. *Structural and Multidisciplinary Optimization*, 48(2):249–265, Aug 2013.

[29] J. Stegmann and E. Lund. Discrete material optimization of general composite shell structures. *International Journal for Numerical Methods in Engineering*, 62(14):2009–2027, 2005.

[30] A. Todoroki and R.T. Haftka. Stacking sequence optimization by a genetic algorithm with a new recessive gene like repair strategy. *Composites Part B: Engineering*, 29(3):277–285, 1998.

[31] S. W. Tsai and N. J. Pagano. Invariant properties of composite materials. In *Composite Materials Workshop*, 1968.

[32] Koetsu Yamazaki. Two-level optimization technique of composite laminate plates by genetic algorithms. pages 212–222, 1997.

[33] S. Zein, P. Basso, and S. Grihon. A constraint satisfaction programming approach for computing manufacturable stacking sequences. *Computers and Structures*, 136:56–63, 2014.

[34] S. Zein and M. Bruyneel. A bilevel integer programming method for blended composite structures. *Advances in Engineering Software*, 79:1–12, 2015.

[35] M. Zhou, R. Fleury, and M. Kemp. Optimization of composite - recent advances and application. 2010.