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OPTIBLESS - AN OPEN-SOURCE TOOLBOX FOR THE OPTIMISATION OF BLENDED STACKING SEQUENCES

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Abstract
A free open-source toolbox for the **Opti**misation of **BLE**nded **S**tacking **S**equences (**OptiBLESS**) is presented in this paper. Despite the increasing use of composite materials over the last decades, optimisation tools for composite structures and stacking sequences remain scarce. While a few proprietary and private software are available for this purpose, there are none in the open source domain where their impact could be greatest. The aim of the developed toolbox presented herein is to provide an accessible and easy-to-use tool for the optimisation of blended stacking sequences. The toolbox capabilities and methodology are addressed in the first part of this paper before being applied to the optimisation of a composite aircraft wing. Results successfully demonstrate the toolbox functionality and performance.

The **OptiBLESS** toolbox is released under a BSD 2-clause license allowing redistribution and use in source and binary forms, with or without modifications. The toolbox, including a user manual and working examples, can be downloaded directly from its GitHub repository:
https://github.com/TMacquart/OptiBLESS.

1. Introduction

The present paper introduces the free open source **Opti**misation of **BLE**nded **S**tacking **S**equences toolbox (i.e. **OptiBLESS**). The toolbox development is motivated first by the absence of such tool in the open source domain and second by the increasing use of composite materials in structural design. Although the benefits of composite materials in structural designs have been highlighted by numerous research works [1–3], optimising composite structures remains challenging and the development of facilitating tools for this purpose has become growing subject of interest [4–8]. One of the most challenging issue facing the development of such tools is the inability to combine high levels of practical manufacturing details with computationally cheap and efficient optimisation methods. While some tools have been proposed in order to address these issues, their potential remain locked as parts of proprietary and private software [9, 10]. By contrast, the toolbox developed by the author provides a free and open-source software facilitating the optimisation of blended stacking sequences.

Stacking sequence optimisation software are critical parts of the composite design process as they bridge the gap between numerical simulations and manufacture. For instance, aircraft wings or wind turbine blades will often be optimised employing stiffness like properties as design variables. These optimised deigns are only intermediaries and equivalent stacking sequences with similar stiffness properties must later be retrieved for these designs to be manufactured. Crucial to their success, stacking sequence optimisation software must include manufacturing design guidelines in order to achieve somewhat realistic

designs and reduce the gap between numerical and manufacturable designs. In order to do so, stacking sequence optimisation software generally rely on direct approaches in which explicit design variables such as fibre angles and the number of plies are used in combination with direct search algorithms [11]. Providing a fair comparison between the various methods for composite optimisation previously proposed in the literature is a challenging task as their performance in terms of design space exploration and computational efficiency are case-dependent. Providing this review is not the objective of this paper. The present paper focuses on the numerical implementation of one of these methods. More precisely, the guide-based approach has been chosen for the **OptiBLESS** toolbox as it offers a concise coding methodology and a one-step optimisation procedure for which the implementation of design guidelines has been successfully demonstrated [6]. The toolbox capabilities and methodologies are discussed in Section 2 while numerical results are presented in Section 3.

2. The OptiBLESS Toolbox

OptiBLESS has been developed in order to facilitate the optimisation of blended stacking sequences including composite design guidelines. To this end, the toolbox regroups and wraps together modules for blended composite design and optimisation. As a result, the current toolbox implementation provides a generic optimisation tool for stacking sequences.

OptiBLESS is a patch-based composite design toolbox where a patch is defined as a region within the structure where the stacking sequence is uniform. Individually optimising the stacking sequences of each patch is likely to result in high level of discontinuities and poor overall structure performance. The toolbox overcome this issue by resorting to a blending strategy. Blending optimisation strategies have been proposed as a means of achieving coherent patch-based composite designs mitigating ply level discontinuities [11]. More precisely, **OptiBLESS** is a numerical implementation of the guide-based blending strategy [5] combined with the generalised blending rule proposed by Van Campen et al. [12]. Under this framework, a stacking sequence is considered blended if the plies of the thinnest laminate patch span the entire structure as shown in Figure 1. The thickest laminate (Lam.1) is defined as the guide and other laminates within the same structure are obtained by dropping ply from the guide. Reciprocally, each ply can also be obtained by adding plies to the thinnest laminate (Lam.3). Note that while all plies from the thinnest laminate span the entire structure they do not need to remain grouped as a bundle of plies and the insertion of in-between plies is allowed.
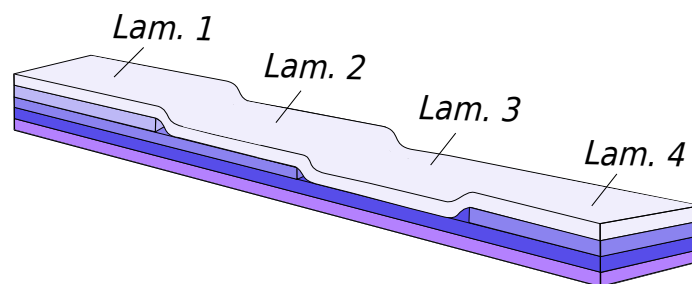

Figure 1. Guide based blending illustration

The toolbox relies on explicit design variables. That is, variables having a direct physical link with the stacking sequence such as fibre angles, ply drops and the number of plies. As a result, typical composite design guidelines can easily be enforced during the optimisation [6, 13]. Guidelines available in **OptiBLESS** are summarised in the list below. During the optimisation, these guidelines are set as constraints and are handled explicitly when possible, otherwise a penalty is incurred to the fitness function.

List of Design Guidelines

- **Symmetry**. The stacking sequence of each patch is mirrored about the mid-plane. Symmetry is often desired as it is a simple method to decouple the in-plane and out-of-plane response of laminates.

- **Balance**. All fibre angles, except 0° and 90°, occur in ± pairs. Similarly to symmetry, balanced laminates are often desired in order to decouple the in-plane normal and shear responses.

- **Damtol**. Damage Tolerance, ±45° plies are used for the upper and lower laminate plies to increse damage tolerance. This is also recommended for buckling performance.

- **Rule10percent**. A minimum of 10% of plies in each of the 0°, ±45° and 90° is enforced. It has been demonstrated that the application of the 10% rule results in robust stacking sequences.

- **Disorientation**. In order for the load-through-thickness to be well distributed, the absolute change of angles between two consecutive plies should not exceed 45°.

- **Contiguity**. In order to avoid microcracking and edge delaminations, the number of consecutive plies with the same fibre angles is limited (set by user).

- **DiscreteAngle**. Discrete fibre angles are used (set by user). While the optimisation of composite structures with arbitrarily small angles is allowed by the toolbox, straight fibres are often available for specific angles such as ± 0,15,30,...,90°.

- **InernalContinuity**. One ply must be maintained spanning the entire structure every 'X' plies (set by user). Internal continuity ensures that a minimum number of plies distributed throughout the thickness spans the whole structures.

- **Covering**. Plies on the lower and upper surfaces of the laminate cannot be dropped in order to prevent edge delamination.

3. Illustrative Example of the OptiBLESS Toolbox

This section demonstrates the application of the **OptiBLESS** toolbox. The common research wing model (CRM) is used as an example.

3.1. Optimisation Problem

The wing's main characteristics, planform, wingbox and operating condition are depicted in Figure 2. The CRM wing lamination parameter design obtained from a previous optimisation work [4] based on the constant operating condition shown in Figure 2 is used as a starting point in this study. The goal is to employ the toolbox in order to retrieve a stacking sequence matching the performance of the lamination parameter wing design while complying with the composite design guidelines. For sake of brevity, only the top skin is considered in this paper. The top skin is divided into twenty laminates each including five design variables. Four in-plane lamination parameters and one thickness variable. The four coupled lamination parameters are zero due to the use of symmetric stacking sequences. Moreover, buckling is not considered and the out-plane lamination parameters are therefore assumed to be zero. Note that this is not a limitation imposed by the toolbox but enforced by the author for sake of brevity. Figure 3 shows the optimised top skin design used as a starting point during our investigation. The corresponding patches normalised polar stiffnesses are plotted on the wing planform. In this example, the wing operates under typical flight conditions for which the wing behaviour is dominated by bending. In order to minimise the wing's mass while providing sufficient bending stiffness, we observe an alignment of the patch fibre angles with the beam axis and a significant reduction of the thickness at the wing tip. Note that the wing

design problem chosen as a starting point in this study is only one possible example and other structures could have equally been used.
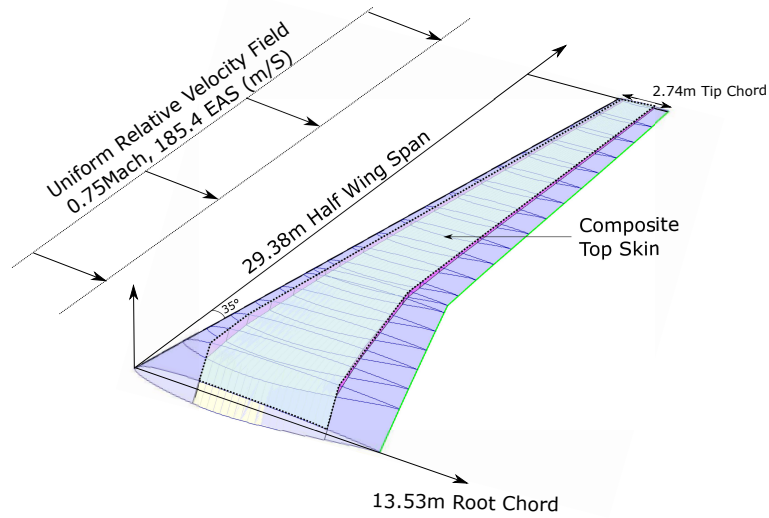

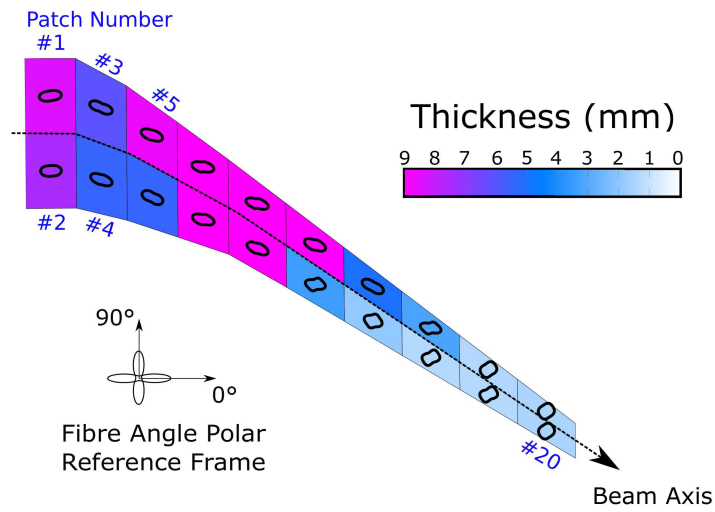**Figure 2.** Common research wing model

Figure 3. Top skin optimised thickness and stiffness, starting point of the stacking sequence optimisation

In order to evaluate and rank the stacking sequences generated during the optimisation, a fitness evaluation function based on the weighted root mean square error ($RMSE$) between the top level lamination parameters given as input $\widetilde{V}$ and the lamination parameters retrieved by the toolbox V is used. The function to minimise is formulated as follows:

$$Fitness = \frac{1}{N_{lam}} \sum_{p=1}^{N_{lam}} RMSE_p \tag{1}$$

$$RMSE_p = \sqrt{\frac{1}{4} \sum_{i=1}^{4} \left(\widetilde{V}_{i,p} - V_{i,p} \right)^2} \qquad (2)$$

where, N_{lam} is the number of laminate patches, $\widetilde{V}_p$ is the vector of input lamination parameters for patch p and V_p is the vector of lamination parameters obtained by the GA. Furthermore, the in-plane lamination parameters are given as

$$V_1 = \frac{1}{N} \sum_{i=1}^{N} \cos(2\theta_i), \ \ V_2 = \frac{1}{N} \sum_{i=1}^{N} \sin(2\theta_i), \ \ V_3 = \frac{1}{N} \sum_{i=1}^{N} \cos(4\theta_i), \ \ V_4 = \frac{1}{N} \sum_{i=1}^{N} \sin(4\theta_i) \qquad (3)$$

where, N is the number of plies in the laminate and θ_i is the fibre angle of ply i.

3.2. Stacking Sequence Optimisation

With the exception of balanced laminates, all design guidelines are enforced. Balanced laminates are not enforced since the lamination parameter optimisation is not restricted to balanced laminates [4]. The contiguity guideline is set such that no more than three consecutive identical ply angles are allowed. Similarly, the internal continuity guideline is set such that no more than three consecutive ply drops are allowed. Furthermore, allowed fibre angles include all multiples of 15°.

The genetic algorithm optimisation options include a fixed size population of 200 individuals running for a maximum of 10000 generations. Regeneration is carried out using a 10% elistim strategy where the best 20 individuals of the previous generation are guaranteed to pass on to the next generation. The crossover probability is set to 75% while the mutation probability is adaptively calculated based on population diversity.

Results of the optimisation are presented in Figures 4, 5 and 6. First, Figure 4 shows a comparison between the input lamination parameters and the lamination parameters retrieved by the toolbox. As it can be observed, the retrieved solution only approximates the input lamination parameters. These matching errors are mainly caused by the discrepancies between the lamination parameter design space and the stacking sequence design space. That is, the retrieved stacking sequence is constrained by the composite design guidelines while the lamination parameter design did not account for any of these guidelines. These constraints also reduce the design search space capabilities of the optimiser making it more likely to generate infeasible designs and, therefore, to converge towards a global optimum. As expected with the lamination parameter matching approach used in this study, we also observe an increase in matching errors as the number of plies reduces. This is a typical problem observed in literature due to the decreasing number of stacking sequence design variables in small laminates.
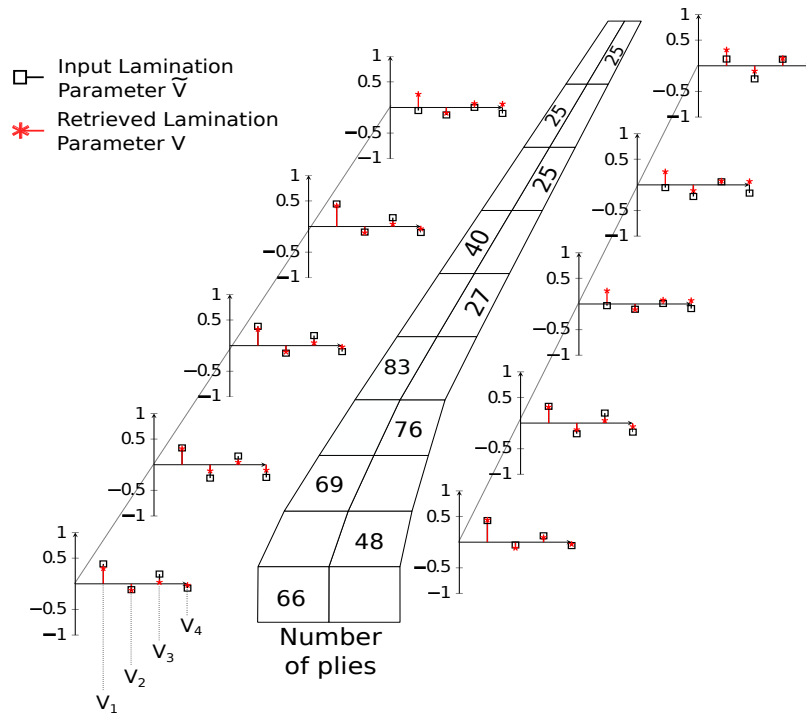
Figure 4. Comparison between input and retrieved lamination parameters

Figures 5 and 6 present the optimised stacking sequence as viewed when running the toolbox. The geometrical stacking sequence layout is displayed in Figure 5 while the stacking sequence details are shown in Figure 6. As observed in these figures, the final design complies with all the enforced guidelines. The internal continuity guideline can easily be identified by the fact that plies spanning the entire structure are distributed throughout the laminate thickness. The 0°, ±45° and 90° plies have been highlighted to show compliance with the 10% rule. Note that in this example the closest integer to 10% is used meaning that four plies of each angle are sufficient to comply with the guideline.

A few critics, subject to improvement in future release of the toolbox, can be made regarding the final design manufacturability and robustness. First, the current implementation of **OptiBLESS** does not include manufacturability restrictions based on ply drops and geometrical information. That is, a ply can be dropped in-between nearby patches as shown by the drop between patch one and five in Figure 6. However, the structure would gain in robustness if the middle patch (i.e. see patch three in Figure 3) was continued from patch one to five. Second, the toolbox does not provide a detailed ply-drop off design for the interfaces between patches. Fortunately, such detailed models can be found in the literature and coupled with the toolbox.

Overall the **OptiBLESS** toolbox successfully retrieved a stacking sequence wing design complying with all the specified composite design guidelines. Additionally, the toolbox is under continuous development as part of an open-source project and the current limitations observed in this study will be addressed in future releases.
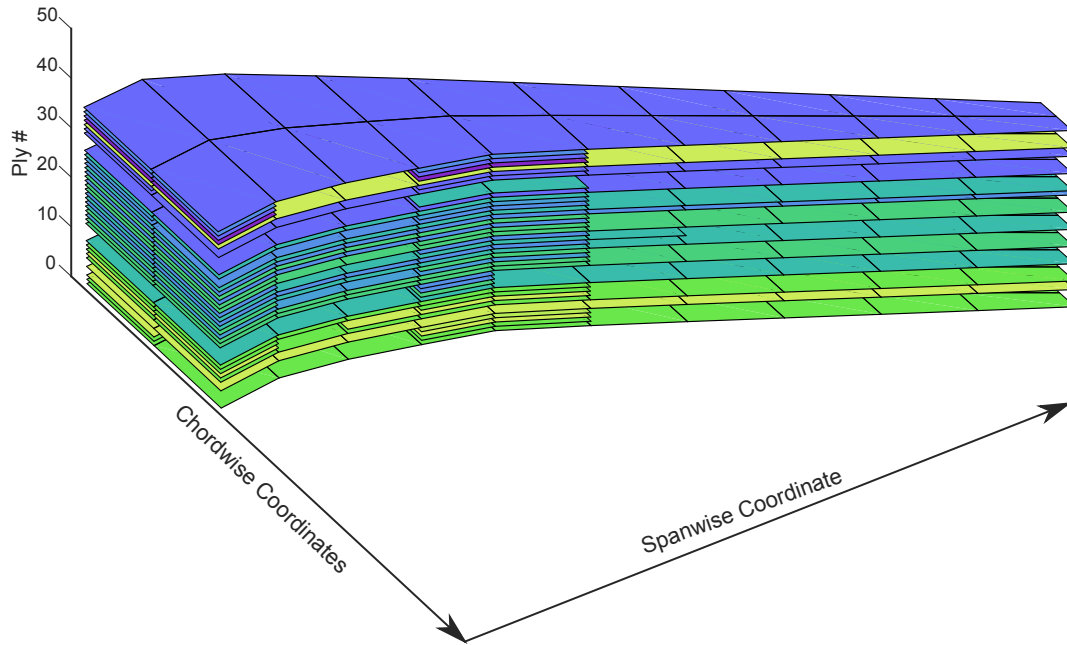
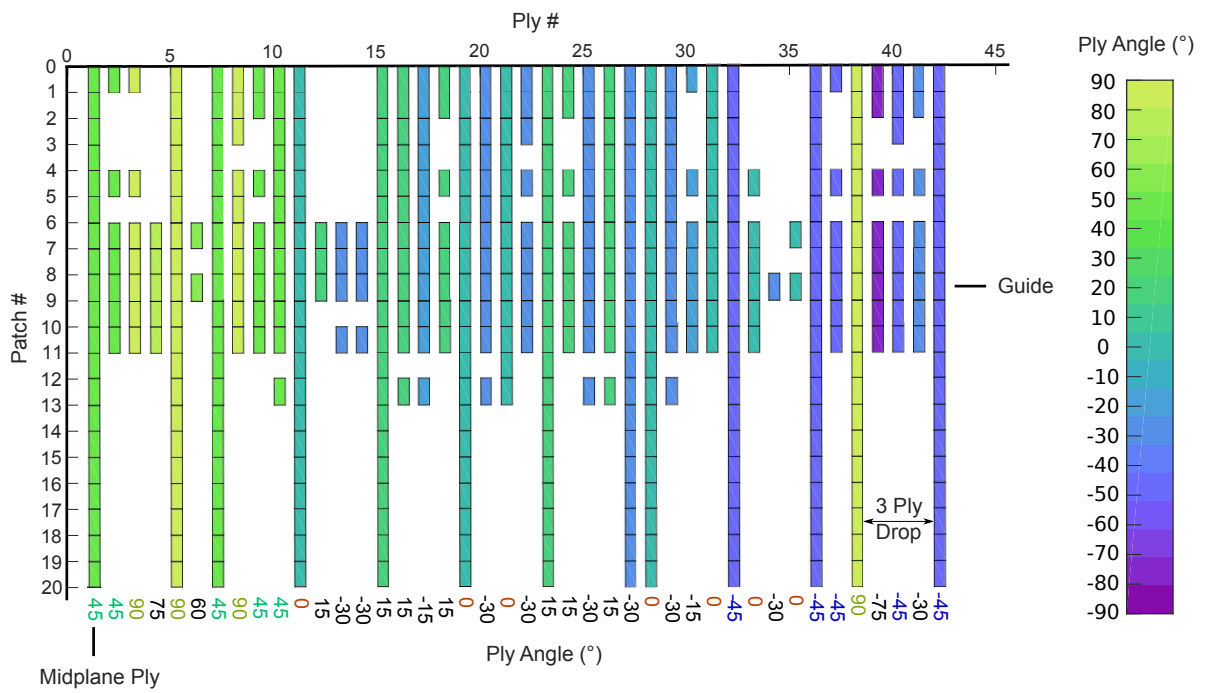**Figure 5.** Top skin stacking sequence optimised by **OptiBLESS**

Figure 6. Top skin detailed stacking sequence optimised by **OptiBLESS**

4. Final Remarks

The free open-source **OptiBLESS** toolbox for the optimisation of blended stacking sequences has been presented in this paper. The developed toolbox combines a guide-based blending strategy with composite design guidelines and with the genetic algorithm provided by the MATLAB optimisation toolbox. While significant progress is still to be made towards the development of a more comprehensive tool for the all-included optimisation of composite structures, the toolbox presented in this paper contributes to this goal by making the first step in developing a free and open source stacking sequence optimisation toolbox.

Acknowledgments

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