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Derivation and application of blending constraints in lamination parameter space for composite optimisation

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ABSTRACT

This article introduces a set of blending constraints expressed in lamination parameter space, applicable during the optimisation of composite structures. Unequal spatial load distributions lead to locally optimised thicknesses and ply orientations. However, ensuring structural continuity during composite tailoring is essential in order to achieve ready-to-manufacture designs. Single step stacking sequence optimisations relying on evolutionary algorithms to enforce continuity through the application of blending rules are prone to the curse of dimensionality. By contrast, multi-step optimisation including a continuous sub-step can optimise composite structures at reasonable computational costs. However, discrepancies between continuous and discrete optimisations result in performance loss during stacking sequence retrieval. This study demonstrates performance improvement during stacking sequence retrieval due to the application of the proposed continuous blending constraints. Numerical results based on the benchmark 18-panel horseshoe blending problem highlight the achievement of near-optimal easy-to-blend continuous designs in a matter of seconds.

1. Introduction

The significant weight saving potential achievable with tailored composite structures is now well-recognised amidst the scientific community. The incentive to manufacture strong yet lightweight structures is also resulting in the increasing use of composite materials in many engineering applications. Moving from metals to composite structures has, however, brought forward a considerable new set of challenges including new failure mechanisms, added complexity and increased number of design variables. These have led to the development of a broad range of composite design guidelines and optimisation methods [1,2].

Over the last decade, it has become evident that optimising composite structures raises several difficulties. Amongst these, the non-convex fibre angle design space, mixed-integer design variables, and manufacturability constraints have been recognised as major obstacles [3,4]. In this paper, the authors focus on one of the manufacturing constraints, namely the blending constraint. First introduced by Kristinsdottir et al. [5], blending is essential to ensure structural continuity and avoid stress concentration during the design of composite structures, where thicknesses and ply orientations are often locally optimised. Single and multi-step optimisations have been proposed to solve the complex problems of composite structure optimisation. Single optimisation methods such as guide-based designs [6] and stacking sequence tables [4] are strictly limited to the generation of designs satisfying blending constraints. Although successful on small scale problems, these approaches result in highly constrained optimisation with prohibitively high computational cost. On the other hand, multi-step algorithms divide the optimisation of composite structures into faster and simpler-to solve sub-optimisation problems [7,8]. Research by Montemurro et al. [9,10] and Catapano et al. [11] proposed a discrete two-level optimisation strategy employing an advanced genetic algorithm (GA). In the first level, each structural part is formulated as a single equivalent homogeneous layer based on polar formalism while matching stacking sequences are retrieved on the second level. Also commonly used are bi-step algorithms which separate the problem into a continuous and a discrete optimisation [12,13]. Employing intermediate design variables (e.g. lamination parameters), the initial problem is reformulated into a continuous convex optimisation for which fast convergence towards a global optimum is guaranteed [14]. Following the first optimisation step, a highly constrained discrete optimisation is usually employed to retrieve ready-to-manufacture

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Notations

$[A]$	membrane stiffness matrix
a_p, b_p	panel dimensions
$[B]$	membrane/bending coupling stiffness matrix
$[D]$	bending stiffness matrix
E^{ip}	in-plane Euclidean distance
E^{oop}	out-of-plane Euclidean distance
$\mathbf{j}$	vector containing the ply-drop locations
$f_k(\theta_j, \theta_i)$	multiplicative coefficient function used for extreme laminates
GA	genetic algorithm
LP	lamination parameters
$\boldsymbol{LP}_{GA}$	lamination parameter vector achieved by the genetic algorithm
$\boldsymbol{LP}_{obj}$	lamination parameter objective vector
N	number of plies
N_{GA}	number of repeated runs of genetic algorithm
m, n	half wave length
SF	safety factor
$\mathbf{S}$	set of dropped plies
t	laminate thickness
X	number of ply-drops between two laminates
X_0	conventional optimised design
X_1	optimised design including blending constraints
X_R	Repaired design
V_1^A, V_2^A, V_3^A, V_4^A	in-plane lamination parameters
V_1^B, V_2^B, V_3^B, V_4^B	coupling in-plane, out-of-plane lamination parameters
V_1^D, V_2^D, V_3^D, V_4^D	out-of-plane lamination parameters
α and β	spherical coefficients
γ	disturbance vector norm
θ, $\boldsymbol{\theta}$	fibre angle(s) (scalar and vector)
λ	buckling factor
ΔV	change in lamination parameters
Δ°	fibre angle step used during stacking sequence retrieval

Subscripts

p	panel number
Ext	extreme laminate: all θ_i are equal to each other and all θ_j are equal to each other

stacking sequences closely matching the continuous optimisation output results [12].

Optimal designs obtained after the first optimisation step generally show the significant improvements achieved by composite structures upon metal-based designs [8]. Nevertheless, retrieving a feasible and manufacture-ready stacking sequence closely matching the continuous results often turns out to be challenging, if not impossible [15]. That is, the manufacturing of composite structures is subject to numerous constraints that are not readily applicable to the continuous parameter spaces used in the first optimisation step (i.e. lamination parameters or polar invariant space). Constraints are most often integrated into the second step in which they are easily handled by evolutionary algorithms. However, running a lightly constrained first step optimisation followed by a highly constrained discrete search can result in high disparities between the two optimisation steps [12,16]. The existence of an equivalent of the optimal first step design existing in the highly constrained design space is therefore not guaranteed. As a consequence, these disparities in design spaces will often result in performance loss of the optimised structure while retrieving a blended stacking sequence. In view of the above, the aim of the present paper is to derive a set of continuous blending constraints in order to achieve more realistic continuous design, and therefore improve performance during stacking sequence retrieval.

The rest of this paper is structured as follows. Section 2 serves as a brief literature review on blending rules. The derivation of blending constraints in lamination parameter space is addressed in Section 3. The proposed constraints are applied to a benchmark optimisation problem in Section 4 while the outputs of this investigation are summarised in Section 5.

2. Blending rules

Various blending definitions have been proposed over the last decade. In their work, Adams et al. [6] consider only inner or outer blending, where the innermost or outermost plies are dropped as shown in Fig. 1a. Van Campen et al. [17] introduce two alternative blending definitions, namely the generalised and relaxed generalised blending as illustrated in Fig. 1b. In the former, two adjacent laminates are blended if all the plies of the thinnest panel are also present in the other panels. Under the relaxed generalised blending definition, two laminates are considered blended if there are no discontinuous plies in physical contact. While the blending constraints proposed in this paper are derived regardless of the blending definitions, the generalised blending definition of Van Campen et al. [17] is used for sake of clarity.

The first application of blending in composite optimisation has been performed by Kristinsdottir et al. [5]. Starting from a set of well-defined in-plane loads, the most loaded panel is identified as the thickest laminate. Laminates from other panels are then obtained by progressively dropping plies from this thickest laminate. This "less-than-or-equal-to" blending rule results in a highly constrained global optimisation problem with mixed-integer variables for which Kristinsdottir et al. [5] proposed an improved hit-and-run optimisation strategy. In another investigation, Liu and Haftka [18] used a constrained bi-level optimisation to enforce continuity. Employing a limited number of ply angles, they

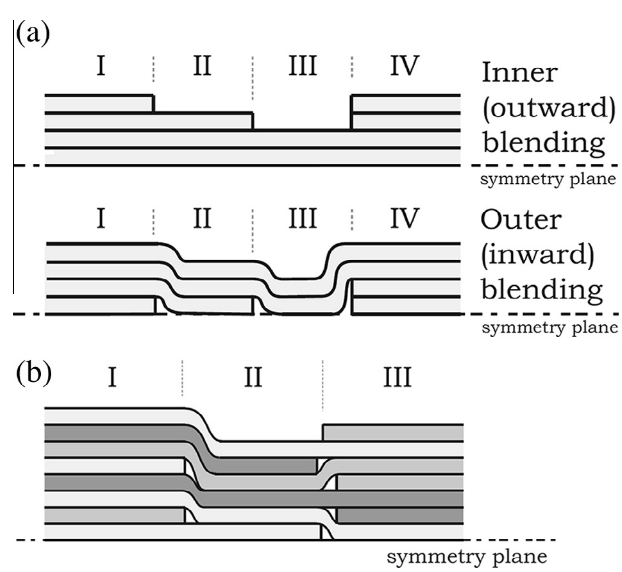

Fig. 1. (a) Outward and inward blending, and (b) generalised (I and II) and relaxed generalised (II and III) blending. Original figures from [17].