Composite Structures 152 (2016) 791–799

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Optimisation of ply drop order in variable stiffness laminates

François-Xavier Irisarri [a,*], Daniël M.J. Peeters [b], Mostafa M. Abdalla [b]

[a] Onera – The French Aerospace Lab, F-92322 Châtillon, France
[b] Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, Delft 2629HS, The Netherlands

ARTICLE INFO

Article history:
Received 25 April 2016
Accepted 23 May 2016
Available online 25 May 2016

Keywords:
Composite optimisation
Variable stiffness
Steering
Blending
Stacking sequence table

ABSTRACT

Modern composite structures offer multiple avenues of optimising performance. One avenue is to optimise a single stacking sequence over the structure leading to constant stiffness designs. Another avenue is to allow the stacking sequence to vary over the structure leading to variable stiffness laminates. This may be achieved either by dropping plies or by steering the fibres. When using ply drops to optimise the thickness distribution two different set of decisions are involved: the selection of ply drop boundaries, and the selection of the ply drop order. In this paper, the fibre angle distribution, the ply drop boundaries, and the ply drop order are simultaneously optimised. The optimisation of fibre angle distribution lends itself easily to gradient based methods. The ply drop boundary optimisation is formulated using topology optimisation techniques and is thus solvable using gradient based methods as well. The ply drop order optimisation requires discrete variables and is hence approached using an evolutionary algorithm based on stacking sequence tables. In this paper an efficient multi-step algorithm is developed to combine the optimisation of all aspects of variable stiffness laminates. The results indicate that significantly improved designs may be obtained by including the ply drop order in the optimisation.

1. Introduction

Composite materials are attractive due to their high stiffness-to-weight and strength-to-weight ratio. It has been shown that by spatially varying the stiffness, even better performance can be obtained without adding extra weight. Varying the stiffness can be done in two ways: either by changing the fibre angles, by steering the fibres, or by changing the number of plies from one point to the next by dropping plies. To develop constant thickness, steered laminates, a three-step optimisation approach has been developed [1,2]. In the first step the optimal stiffness distribution in terms of lamination parameters is found, in the second step the optimal fibre angles are obtained, and in the third step the optimal fibre paths are retrieved. A thickness variation has already been implemented in the first step of the optimisation, and showed that significant improvements could be obtained, however, no information about fibre angle or number of plies is available at the first step, so the physical construction of the laminate remains to be found. A method to optimise the fibre angle and ply drop locations has recently been developed, but the ply drop sequence was pre-specified [3].

Thickness variation in a laminate is described using two variables: the ply drop location and the ply drop order. The most popular approach is to use an evolutionary algorithm, typically a genetic algorithm, to optimise the number of layers per 'patch', while also optimising the ply drop order and stacking sequence, limited to a discrete set of angles (e.g., 0°, ±45°, and 90°). This area of research is referred to as laminate blending [4–8] and assumes that potential ply drop locations (i.e., patch boundaries) are pre-specified by the user. A technique where the fibre angle is not restricted to a discrete set has also been developed, however, no manufacturing constraints, limiting the change in fibre angle from one element to the next, are posed [9].

Other techniques where the ply drop locations are not pre-specified use continuous optimisation. Shape optimisation [10] is used to determine the shape and hence ply coverage and ply drop locations of the different layers. The optimisation is performed using a level-set approach with fibre angles limited to a discrete set. Another continuous method is the discrete material and thickness optimisation method, where the fibre angles belong to a discrete set and fictitious density variables are used to select the ply angles at any given location. This has been done for compliance and buckling optimisation [11,12]. For this method, also a thickness filter has been implemented to get to physically feasible designs [13]. Thickness optimisation for buckling load under uni- and bi-axial compression has also been performed. This work

---

* Corresponding author.
E-mail address: francois-xavier.irisarri@onera.fr (F.-X. Irisarri).

http://dx.doi.org/10.1016/j.compstruct.2016.05.076
0263-8223/© 2016 Elsevier Ltd. All rights reserved.

showed that large improvement in buckling load could be made without affecting the in-plane stiffness [14].

The easiest ply drop orders are inner or outer blending, where the layers are dropped from the symmetry plane, or from the outside respectively. To determine the optimal ply drop order, guide-based designs can be used: Adams et al. [5] a stacking sequence for the thickest laminate, called the guide laminate, is defined and the number of layers per patch. The stacking sequence is then derived by dropping layers from the inside or outside, depending whether inner or outer blending is used, from the guide laminate. A method that offers more possible ply drop orders and takes into account industrial guidelines is using stacking sequence tables [15]. A ply drop order and guide laminate are optimised.

This paper aims to combine the ideas behind the optimisation of optimising ply drop locations and the stacking sequence tables [15,3]. The outcome will be an optimal steered, variable thickness laminate: both the ply drop location and ply drop order are optimised. The remainder of the paper is organised as follows: first the general approach is explained in Section 2, next the ply drop location optimisation is discussed in Section 3, followed by a description of the stacking sequence tables in Section 4, some numerical examples in Section 5 and finally a conclusion in Section 6.

2. Approach

The overall optimisation strategy is based on the three step optimisation approach developped by IJsselmuiden [1]. The present work focuses on the second step of the optimisation and combines the optimisation of the spatial distribution of the fiber angles and the optimisation of the ply drop location and ply drop order. Fig. 1 gives an overview of the proposed optimisation approach. Step 1 (see [16,17,2]) returns an *idealized design* defined as an optimal stiffness and thickness distribution over the structure. The idealized design gives an upper bound of the performance of the structure.

In the proposed approach, Step 2 is subdivided into two successive optimisation phases referred to as Step 2.1 and Step 2.2 respectively. Both phases combine an evolutionary optimiser and a gradient-based optimizer for their complementary efficiency in solving combinatorial problems and continuous problems respectively.

Step 2.1 aims at providing a relevant initial guess of the fibre angle distributions per ply, total thickness distribution and ply drop order for the subsequent optimisation phase. Step 2.1 takes as input the idealized design obtained from Step 1. The thickness distribution is set to the *rounded* idealized thickness distribution and a stiffness matching optimisation is performed targeting the idealized stiffness distribution. A Pareto multi-objective evolutionary optimiser is used to match the membrane stiffness distribution and the bending stiffness distribution of the idealized design. The optimiser returns a set of straight fiber solutions, each one defined by a Stacking Sequence Table (SST), meaning a guide laminate and a ply drop order. The non-dominated solutions from the EA are used as starting points for a subsequent gradient-based optimisation. Here the spatial distribution of the variation of fibre angles in each ply, and a *continuous* thickness distribution are found over the structure. At this stage, the designs have realistic fibre angle and ply drop designs but non-manufacturable continuous thickness.

Step 2.2 aims at converting the laminate thickness distributions into properly defined ply drop locations. The optimisation is initialized with the non-dominated front issued from Step 2.1. An evolutionary algorithm (EA) specialized for ply drop order optimisation is hybridized with a gradient-based method devised for ply drop location optimisation. For each ply drop order generated by the EA, a topology-like optimisation is performed using a fictitious density distribution for each ply. The densities are forced to converge to either one or zero which defines the ply coverage and the ply drop locations. The gradient based optimisation alternates between density optimisation and fiber angle optimisation in each ply.

3. Fibre angle optimisation and ply drop location optimisation

In structural optimisation, the minimisation of an objective response (e.g., weight or compliance) subject to performance constraints (e.g., on stresses or displacements) is studied. More generally, the worst case response, for example in the case of multiple load cases, is optimised. Additional constraints not related to structural responses may also be imposed to guarantee certain properties of the design such as manufacturability. The following general problem formulation is considered:

$$\begin{aligned} \min_{\vec{\rho},\vec{\theta}} \quad & \max(f_1, f_2, \ldots, f_n) \\ s.t. \quad & f_{n+1}, \ldots, f_m \leqslant 0 \\ & V \leqslant \eta \cdot V_0 \\ & \vec{\rho}, \vec{\theta} \in \mathscr{D}_i \end{aligned} \tag{1}$$

where V is the material volume, η is the maximum allowed volume fraction, and V_0 is the total domain volume. The functions f_i depend

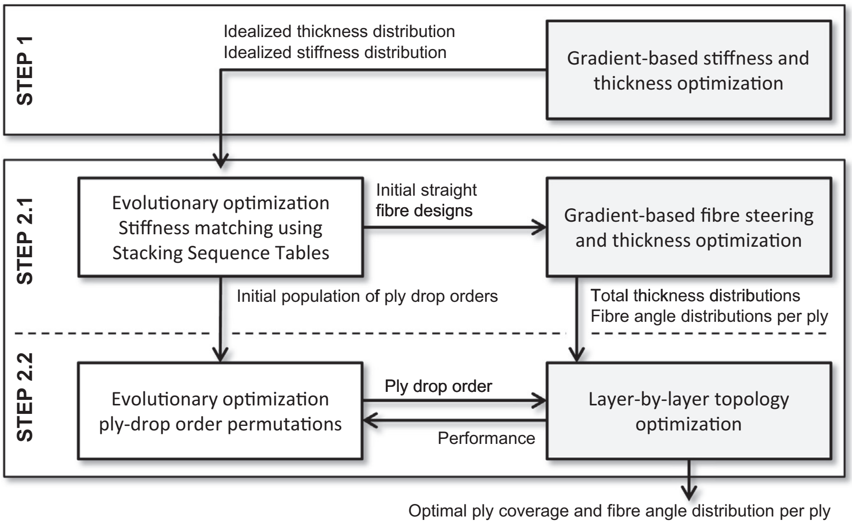

Fig. 1. Overview of the optimisation strategy.