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Effect of steering limit constraints on the performance of variable stiffness laminates ☆

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ABSTRACT

A method to optimise the fibre angle distribution of variable stiffness laminates is proposed. The proposed method integrates a fibre angle retrieval step with a fibre angle optimisation procedure. A multi-level approximation approach is used in combination with the method of successive approximations. First, fibre angle retrieval is done by approximating the structural responses based on the optimal stiffness distribution found using lamination parameters. The full fibre angle optimisation is done by updating the approximations based on the current stacking sequence. Next, the actual fibre paths are optimised taking into account the actual size of a tow, and the maximum size of any gap or overlap appearing. The paths are smoothed out using CATIA, and finally spline curves are found that can be sent to a fibre placement machine for manufacturing. It is shown for a bucking optimisation with a stiffness constraint that the number of finite element analyses reduces significantly by starting the optimisation from the optimal stiffness distribution rather than from a user-specified stacking sequence. Next, it is shown that updating the approximations also leads to considerable improvements over fibre angle retrieval. Similar promising results are obtained for a stress optimisation problem.

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1. Introduction

Today, composite materials are finding increasing application in large commercial aircraft and the first composite-dominated planes like the B-787 or A400M are being built. Traditionally, fibres within a layer have the same orientation, leading to constant stiffness properties. As manufacturing technology has evolved, for example the advent of automated fibre placement machines, the fibre orientation of a layer can be varied continuously leading to varying stiffness properties that can be best tailored for the applied loads. These composites are called variable stiffness laminates (VSL) in the current work.

One of the largest problems in optimising VSL, is taking manufacturability into account. To do this, linearly varying fibre angles are used by many researchers, which has given promising, manufacturable, results [1–17]. The use of linearly varying fibre angle per bay, for stiffened plates, has also been investigated, and again it has been shown that varying the fibre angles leads to better performance [18,19]. Additional direct parametrisation of the tow paths using Lagrangian polynomials [20–22], Lobatto-Legendre polynomials [23,24], Bezier curves [25–27], splines [28,29], B-splines surfaces [30] and NURBS (Non-Uniform Rational B-Splines) [31] are found in the literature. Constant curvature paths have been extensively applied for flat panels and for cylindrical and conical shells [32–36], as the curvature constraint evaluation is simplified. Large, manufacturable, improvements in buckling load were found, but the result is dependent of the basis functions chosen [31,37,20]. Hence, the total potential of VSL has not been exploited due to the pre-specified set of possibilities. Furthermore, most methods assume that the fibres are shifted, meaning a choice had to be made whether gaps or overlaps are allowed during manufacturing [38]. For instance, gaps and overlaps are observed in the cylindrical shells manufactured by Wu et al. [32] and the flat plates manufactured by Tatting and Gürdal [7].

Another approach that leads to manufacturable designs is to align the fibres in the direction of principal stress. This has been shown to reduce stress concentrations, and can also lead to reduced weight using the tailored fibre placement method [39,40]. Using load paths, or a hybrid combination of load paths and principal stress direction has also been used to design VSLs [41]. Continuous tow shearing is a new manufacturing method,

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leading to varying fibre angles without any gaps or overlaps, but with a thickness variation that is coupled with the change in fibre angle [42,27]. By using a genetic algorithm, coupled with a pattern-search algorithm, or using the infinite strip method, large improvements in structural performance have been shown [43,44]. A more comprehensive review of optimisation strategies can be found in Ghiasi et al. [45].

For laminate analysis, studies have been conducted on capturing the influence of as-manufactured geometry and features such as gaps, overlaps, tow-drops and variable thickness for the analysis of VSL, by means of 3D FE models [10,33,46–52], analytical methods [53]and experimental tests[50,54–58]. Some experiments support the use of overlaps over the tow-drop method for strength and buckling [9,32,33,59]. In addition, experimental tests on flat coupons where carried out by Croft et al. [54] to evaluate the effect of individual manufacturing-induced defects, such as gaps, overlaps and twisted tows. They found that usually defects (gaps or overlaps) that improve one mechanical property also deteriorate another one. Blom et al. [60] proposed a method to optimise the course locations for minimum ply thickness and maximum surface smoothness.

Other manufacturing features are considered in design, such as minimum curvature radius [58,61–66] and minimum cut length [57]. A review focused on analysis methods for buckling, failure and vibration was published by Ribeiro et al. [67] and on design for manufacturing by Lozano et al. [68].

To exploit the possibilities of VSL fully, a three-step approach has been developed. The first step is to find the optimal stiffness distribution in terms of the lamination parameters. This is discussed in detail in IJsselmuiden [64,69]. The second step is to find the optimal manufacturable fibre angle distribution, the focus of this paper [70–72]. The third step is to retrieve the fibre paths, discussed in Blom [60]. A schematic overview of this approach is shown in Fig. 1.

The lamination parameters are optimised in step one of the three-step optimisation approach, which has the disadvantage that a fibre angle retrieval step is needed. Enumeration has been used for constant stiffness laminates to match lamination parameters in terms of fibre angles [73]. If the number of layers gets too high, a layer-wise optimisation approach might have advantages: first, the outer layer(s) are optimised, then the optimisation moves inward [74]. Also a genetic algorithm (GA) is sometimes used for variable stiffness laminates to retrieve fibre angles from the optimal lamination parameter distribution. Due to the computational cost of a GA, this is limited to a relative small number of variables [75,76]. An approach closely related to the three-step approach is proposed by Wu et al., who first optimise the lamination parameters, followed by a retrieval step using a GA and Lagrangian polynomials. However, no manufacturing constraints are taken into account during the second step, hence the results found are not guaranteed to be manufacturable [77]. Another approach is to try to match the in- and out-of-plane matrices as closely as possible using a combination of a GA and a modified Shepard's interpolation [78]. In other work, a real retrieval step was performed: the fibre angles were optimised using a combination of a GA and a gradient based optimiser to match the optimal stiffness distribution as closely as possible, while obeying a steering constraint [4]. Several authors have employed a streamline analogy, also known as a fluid flow analogy, to compute continuous fibre paths from discrete fibre angles [41,23,59,79–82].

In this paper, a method is discussed which combines fibre angle retrieval and fibre angle optimisation. First, the angles are retrieved based on the optimal stiffness distribution; next, starting from this fibre angle distribution, fibre angle optimisation is performed. The paper is organised as follows: the optimisation approach is explained in Section 2, after which the solution procedure is explained in Section 3. The post-processing approach, where the actual fibre paths are found, is explained in Section 4. Then, two examples are worked out in more detail: a buckling optimisation example in Section 5 and a stress optimisation in Section 6. The paper is concluded in Section 7.

2. Optimisation approach

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:

$$\begin{aligned} \min_{\mathbf{x}} \quad & \max(f_1, f_2, \dots, f_n) \\ s.t. \quad & f_{n+1}, \dots, f_m \leqslant 0 \\ & x \in \mathcal{D} \end{aligned} \tag{1}$$

The functions f_i depend on the design variables; f_1 to f_n denote structural responses that are optimised and f_{n+1} to f_m denote structural responses that are constrained. The feasible region is denoted by $\mathcal{D}$. This problem will be solved using successive approximations: one starts from a certain fibre angle distribution, constructs the approximations based on the optimal stiffness distribution, optimises the approximations and updates the approximations based on the new fibre angles. This is repeated until convergence is reached.

Structural responses, such as buckling loads, stiffness, and strength, are calculated using finite element (FE) analysis. Since each FE analysis is computationally expensive, greater efficiency can be achieved by using structural approximations to reduce the required number of FE analyses [83,65]. The exact FE response f is approximated in terms of the in- and out-of-plane stiffness matrices $\boldsymbol{A}$ and $\boldsymbol{D}$ and their reciprocals [64]:

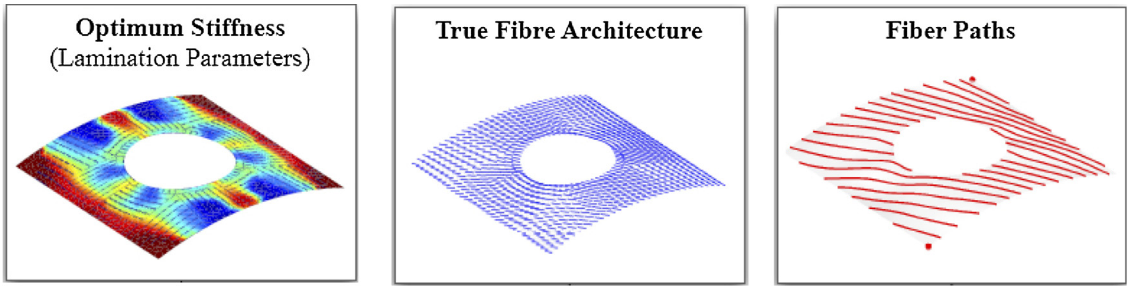

Fig. 1. Schematic overview of the three-step optimisation approach [64].

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