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A general multi-scale design strategy for the optimisation of variable stiffness composites

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Abstract

The present paper focuses on the development of a multi-scale design strategy for the optimisation of variable angle stiffness laminates. The main goal consists in proving that it is possible to design structures having complex shapes made of variable stiffness composites by taking into account, from the early stages of the design process, the constraints linked to the manufacturing process.

Introduction

Anisotropic materials, such as fibre-reinforced composite materials, are extensively used in many industrial fields thanks to their mechanical performances: high stiffness-to-weight and strength-to-weight ratios that lead to a substantial weight saving.

In addition, the recent development of new manufacturing techniques of composite structures, e.g. automated fibre-placement (AFP) machines, allows for going beyond the classical design rules, thus leading the designer to find innovative and more efficient solutions than the classical straight fibres configurations. The use of the AFP technology brought to the emergence of a new class of composite materials: the variable angle tow (VAT) composites (Gurdal 2008, Catapano 2013). A modern AFP machine allows the fibre (i.e. the tow) to be placed along a curvilinear path within the constitutive lamina thus implying a point-wise variation of the material properties (stiffness, strength, etc.). Of course, this technology enables the designer to take advantage of the directional properties of composites in the most effective way. Although the utilisation of VAT laminates considerably increases the complexity of the design process (mainly due to the large number of design variables involved within the problem), on the other hand it leads the designer to conceive non-conventional solutions characterised either by a considerable weight saving or enhanced mechanical properties when compared to classical solutions, (Nagendra 1995, Nik 2012). The complexity of the design process of a VAT laminated structure is mainly due to two intrinsic properties of VAT composites, i.e. the heterogeneity and the anisotropy that intervene at different scales of the problem and that vary point-wise over the structure. Moreover, a further difficulty is due to the fact that the problem of (optimally) designing a VAT laminate is intrinsically a multi-scale design problem. Indeed, in order to formulate the problem of designing a VAT composite in the most general way, the designer should take into account, within the design process, the full set of design variables (geometrical and material) governing behaviour of the structure at each characteristic scale (micro-meso-macro). Up to now no general rules and methods exist for the optimum design of VAT laminates. The few works that can be found in literature always make use of some simplifying hypotheses and rules to get a solution. As a summary of this brief review it can be stated that the main limitations and drawbacks characterising the vast majority of the studies on VAT laminates are:

- the use of linear functions for representing the fibre path (which significantly reduces the design domain);
- the lack of a multi-scale approach for dealing with the (optimal) design problem of VAT laminates;
- the absence of practical rules for taking into account the manufacturability/technological constraints since the early stages of the design process;
- the applications which are limited only to "academic" cases and not extended to real-world engineering problems.

To overcome the previous restrictions the present work will focus mainly on the generalisation and extension of the multi-scale bi-level (MS2L) procedure for the optimum design of composite structures (Montemurro 2012, Montemurro 2016) to the case of VAT composites. Up to now this strategy has been employed only by few authors for the optimisation of composite structures but in each study the link between the levels of the procedure and the scales of the problem was never rigorously stated.

Description of the strategy

The main goal of the design strategy is the optimum design of a VAT laminated plate subject to constraints of different nature, i.e. mechanical, feasibility and manufacturability constraints. The optimisation procedure is articulated into the following two distinct (but linked) optimisation problems.

First-level problem. The aim of this phase is the determination of the optimum distribution of the material properties of the structure in order to minimise the considered objective function and to meet, simultaneously, the full set of optimisation constraints provided by the problem at hand. At this level the VAT laminate is modelled as an equivalent homogeneous anisotropic continuum whose behaviour at the macro-scale is described in terms of laminate polar parameters, (Verchery 1979).

Second-level problem. The goal is the determination of the optimum lay-up of the VAT laminate (the laminate meso-scale) meeting the optimum combination of their

material parameters provided by the first level of the strategy (for each point of the plate). At this stage, the design variables are the layer orientations and the designer can add some additional requirements, e.g. constraints on the elastic behaviour of the laminate, manufacturability constraints, strength and damage criteria, etc.

In order to improve the MS2L optimisation strategy and generalise its application to the case of VAT laminates some mayor modifications have been introduced. Regarding the first step of the strategy, the following changes have been made:

- the shear stiffness of the laminate is now taken into account through the use of the polar method applied to the FSDT (Montemurro 2015);
- the point-wise variation of the laminate material design variables is expressed through B-spline hyper-surfaces.

The first point represents a very important step forward in the MS2L strategy when applied to every kind of composite structure (classical or VAT) as it allows to properly design thin as well as moderately thick plates. The second modification leads to important consequences too (representing several advantages in solving the optimisation problem). Firstly the use of iso-geometric hyper-surfaces allows reducing the number of design variables (in this case the variables are the material parameters defined solely on the points of the control network of the hyper-surface). Moreover, thanks to a special property of this class of parametric surfaces (the *strong convex hull property*) it is possible to impose the optimisation constraints only in each control point: if they are satisfied on the control net they are automatically met over the entire surface.

The second-level problem consists in determining at least one stacking sequence satisfying the optimum values of the polar parameters resulting from the first level of the strategy and having the elastic symmetries imposed on the laminate within the formulation of the first-level problem, i.e. quasi-homogeneity and orthotropy.

In the case of a VAT laminate the fibre orientation varies point-wise in every constitutive ply. Therefore a proper description of the fibres path is necessary to formulate and solve the second-level problem of the MS2L strategy. To this purpose, the modifications introduced in the second level of the MS2L strategy are the following ones:

- the point-wise variation of the fibre orientation (in each ply) is described through the use of B-spline hyper-surfaces;
- the reconstruction of the fibres path is achieved through an analogy with the problem of the streamlines (typical problem of fluid mechanics);
- the technological constraint on the minimum radius of curvature of the tows is integrated within the strategy.

These improvements lead to important advantages in solving the design problem of VAT laminates. In fact, the use of B-spline hyper-surfaces allows, like in the first step of the strategy, to reduce the total number of design variables: in this case the fibre orientations are defined solely at each control point. In addition, the utilisation of B-spline blending functions allows finding, analytically

and in a very simple manner, the expression of the radius of curvature of the fibres path. This information leads the designer to proper formulate the optimisation problem of VAT composites by integrating the manufacturing constraint directly within the design/optimisation process in an easy and efficient way.

Studied cases

The optimisation strategy presented in this study is applied to a laminated plate composed of a fixed number of plies. The fibre tow is made of carbon-epoxy material. A bi-axial compressive load per unit length is applied on the plate edges with $N_y = \alpha N_x$. The goal is the maximisation of the buckling load of the structure by satisfying, simultaneously, constraints of different nature: mechanical, geometrical, technological, etc. The design variables are the layers orientation angles defined point-wise over the plate. Numerical results show that it is possible to obtain an optimum solution meeting all the imposed requirements and having a buckling load equal to two times that of a standard aeronautical stacking sequence (straight fibres).

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