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On the effective integration of manufacturability constraints within the multi-scale methodology for designing variable angle-tow laminates

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ABSTRACT

In this work a multi-scale two-level (MS2L) optimisation strategy for optimising VAT composites is presented. In the framework of the MS2L methodology, the design problem is split and solved into two steps. At the first step the goal is to determine the optimum distribution of the laminate stiffness properties over the structure (macroscopic scale), while the second step aims at retrieving the optimum fibres-path in each layer meeting all the requirements provided by the problem at hand (mesoscopic scale). The MS2L strategy has been improved in order to integrate all types of requirements (mechanical, manufacturability, geometric, etc.) within the first-level problem. The proposed approach relies on: (a) the polar formalism for describing the behaviour of the VAT laminate, (b) the iso-geometric surfaces for describing the spatial variation of both the laminate stiffness properties (macro-scale) and the layers fibres-path (meso-scale) and (c) an hybrid optimisation tool (genetic and gradient-based algorithms) to perform the solution search. The effectiveness of the MS2L strategy is proven through a numerical example on the maximisation of the first buckling factor of a VAT plate subject to both mechanical and manufacturability constraints.

1. Introduction

Anisotropic materials, such as fibres-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 when compared to metallic alloys. 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 fibre configurations. The use of the AFP technology brought to the emergence of a new class of composite materials: the variable angle tow (VAT) composites, [1,2]. 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. The interest of using variable stiffness (VS) laminates is considerably increased during the last years: in the meantime some works on the *a posteriori* characterisation of the elastic response of such materials have gained a lot of attention from the scientific community of composites materials, [3,4]. 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, [5–8]. One of the first works that tried to explore the advantages that can be achieved in terms of mechanical performances (stiffness, buckling behaviour, etc.) by using a VS plate in which each ply is characterised by a curvilinear path of the tow (i.e. a VAT configuration) instead of the conventional straight fibre format is presented in [2]. The authors make use of a sensitivity analysis and a gradient-based search technique to determine the optimal fibre orientation in a given number of regions of the plate. This work proved that a considerable increment of the buckling load of the structure can be obtained when employing a VAT solution for the layered plate.

The complexity of the design process of a VAT laminated structure is mainly due to two intrinsic properties of VAT composites,

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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 multi-scale nature of the design problem: in the most general case, the designer should take into account, within the same process, the full set of design variables (geometrical and material) governing the 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. Only few works on this topic can be found in literature, and all of them always make use of some simplifying hypotheses and rules to get a solution. An exhaustive review focusing on the design of constant as well as VS composite laminates is presented in [9,10]. In [11] the first natural frequency of VS composite panels is maximised by considering on the one hand the lamination parameters and the classical laminate theory (CLT) for the description of the local stiffness properties of the structure and, on the other hand, a generalised reciprocal approximation algorithm for the resolution of the optimisation problem. This approach is limited to the determination of the stiffness properties of an equivalent homogeneous plate, since the lay-up design phase is not at all considered. In [12] the least-weight design problem of VAT laminates subject to constraints including the strength and the radius of curvature is considered. The design variables are the layers thickness and fibres angles which are represented by bi-cubic Bezier surfaces and cubic Bezier curves, respectively. A sequential quadratic programming method is used to solve the optimisation problem.

A two-level strategy was employed in [13] to design a VAT laminated plate: this work represents the first attempt of applying a multi-scale numerical strategy which aims at determining, at the first level, the optimum distribution of the stiffness properties of the structure (in terms of the lamination parameters of the laminate), and at the second level the optimum path (in each constitutive layer) matching locally the lamination parameters resulting from the first step. However, the major drawback of this work actually was in the determination of the curvilinear fibres-path of each layer: the resulting path was discontinuous because the authors had not foreseen a numerical strategy able to simultaneously meet on the one hand the continuity of the fibres path (between adjacent elements) and on the other hand the optimum distribution of lamination parameters provided by the first step of the procedure. In [14] the two-level approach was abandoned and the authors stated the problem by directly considering the parameters governing the shape of the fibres-path in each ply as design variables. However, as in [11], this approach always leads to a discontinuous fibres-path and, unlike the strategy proposed in [11], it leads also to the emergence of a new issue: the resulting optimisation problem was highly non-convex since it was formulated directly in the space of the layers orientations. Accordingly, in [14] the authors conclude that such an issue can be potentially remedied by formulating in a proper way the design problem of VAT laminates in the framework of the two-level strategy and by trying to overcome the issue of the continuity of the fibres-path directly in the first level of the strategy where the design variables are the laminate mechanical properties (e.g. the lamination parameters as in the theoretical framework of [13]).

Another issue often addressed by researches on VAT laminates concerns the tow placement technology which could introduce several differences (i.e. imperfections) between the numerical model of the VAT composite and the real structure tailored with the AFP process, if the design methodology does not take into account the manufacturability requirements. To this purpose in [15] an issue linked to the AFP technology is addressed: the overlap of tow-placed courses that increases the ply thickness (the build-up phenomenon) thus affecting the structural response and the surface quality of the laminate. The work of Blom et al. [15] presents a method for designing composite plies with varying fibres angles. The fibre angle distribution per ply is given while, using a streamline analogy, the optimal distributions of fibres courses is determined for minimising the maximum ply thickness or maximising the surface smoothness. An improved research on this topic has been developed in [16] where an algorithm is presented to optimise the fibres path for ensuring manufacturability. A further work focusing on the development and/or improvement of manufacturing techniques for tailoring VAT laminates in order to minimise the imperfections induced by the fabrication process is presented in [17]. The continuous tow shearing (CTS) technique, utilising the ability to shear dry tows, is proposed as an alternative technique to the well-known AFP process. Later, the work presented in [17] has been improved through the introduction of a computer-aided modelling tool [18] which can create accurate finite element models reflecting the fibre trajectories and thickness variations of VAT composites manufactured using the CTS technique.

To overcome the previous restrictions, recently the authors presented in [19] a first work focused on the generalisation and extension of the multi-scale bi-level (MS2L) procedure for the optimum design of composite structures (initially introduced in [20,21]) to the case of VAT composites. Such a MS2L procedure has already been employed by the authors and their co-workers in the past for the design and optimisation of several classes of hybrid anisotropic structures [20–27]. The MS2L design strategy is characterised on the one hand by the refusal of simplifying hypotheses and classical rules usually employed in the framework of the design process of laminates, and on the other hand by a proper and complete mathematical formalisation of the optimum design problem at each characteristic scale (meso-macro). The MS2L strategy relies on the use of the polar formalism (initially introduced by Verchery [28], and later extended to the case of higher-order theories by Montemurro [29–31]) for the description of the anisotropic behaviour of the composite. The real advantage in using the Verchery's polar method is in the fact that the elastic response of the structure at the macro-scale is described in terms of tensor invariants, the so-called *polar parameters* having a precise physical meaning (which is linked to the elastic symmetries of the material) [32]. On the other hand the MS2L strategy relies on the use of a particular genetic algorithm (GA) able to deal with a special class of huge-size optimisation problems (from hundreds to thousands of design variables) defined over a domain of variable dimension, i.e. optimisation problems involving a "variable number" of design variables [25].

As far as concerns the problem of designing VAT composites, in [19] several modifications have been introduced in the theoretical and numerical framework of the MS2L design procedure at both first and second levels. At the first level (laminate macroscopic scale) of the procedure, where the VAT laminate is modelled as an equivalent homogeneous anisotropic plate whose mechanical behaviour is described in terms of polar parameters (which vary locally over the structure) the major modifications concerned: (1) the utilisation of higher-order theories (First-order Shear Deformation Theory (FSDT) framework [29,30]) for taking into account the influence of the transverse shear stiffness on the overall mechanical response of VAT composites; (2) the utilisation of B-spline surfaces for obtaining a continuous point-wise variation of the laminate polar parameters. Regarding the second-level problem (laminate mesoscopic scale, i.e. the ply level) the main modifications were: (1) the utilisation of B-spline surfaces for obtaining a continuous point-wise variation of the fibres-path within each ply; (2) a proper mathematical formalisation of the manufacturability constraints linked to the AFP process in the framework of the B-spline representation. All of these modifications imply several advantages for the resolution of the related optimisation prob-