Une nouvelle méthodologie de conception multi-échelle pour l'optimisation des composites à rigidité variable

A new multi-scale design methodology for the optimisation of variable stiffness composites

Marco Montemurro[1], Anita Catapano[2]

1 : IMC, I2M CNRS UMR 5295
Arts et Métiers ParisTech
Esplanade des Arts et Métiers, F-33400 Talence Cedex
e-mail : marco.montemurro@ensam.eu

2 : IMC, I2M CNRS UMR 5295
Bordeaux INP, Université de Bordeaux
351 cours de la Libération, F-33405 Talence Cedex
e-mail : anita.catapano@bordeaux-inp.fr

Résumé

Ce travail propose une méthodologie originale pour l'optimisation multi-échelle des composites à rigidité variable (CRV) capable d'intégrer, dès l'étape de conception préliminaire, les contraintes technologiques liées au procédé placement filamentaire automatisé (PFA). Plus précisément, une stratégie multi-échelle à deux niveaux (MS2L) pour l'optimisation des CRV est présentée dans ce travail. Dans le cadre de la méthode MS2L, le problème de conception est décomposé en deux sous-problèmes distincts. Lors de la première étape (optimisation structurale), le but est de déterminer la distribution spatiale optimale des paramètres de rigidité du CRV à l'échelle macroscopique (le stratifié CRV est modélisé comme une plaque homogène anisotrope équivalente dont les propriétés mécaniques varient ponctuellement), tandis que la deuxième étape (*lay-up design*) vise à retrouver le chemin optimal des fibres dans chaque pli du stratifié (échelle mésoscopique) tout en respectant les paramètres mécaniques optimaux issus de la première étape. L'approche proposée repose sur l'utilisation : a) du formalisme polaire généralisé au cas de la théorie FSDT (*first-order shear deformation theory*), b) de surfaces iso-géométriques pour décrire la variation spatiale des paramètres de rigidité du stratifié (échelle macroscopique) ainsi que du chemin des fibres dans les plis (échelle mésoscopique) et c) d'un outil d'optimisation hybride (algorithme génétique + algorithme au gradient) pour effectuer la recherche des solutions. L'efficacité de la stratégie MS2L est prouvée via un exemple numérique sur la maximisation de la première charge critique d'une plaque CRV soumise à des contraintes mécaniques, géométriques et technologiques liées au procédé PFA.

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.

Mots Clés : stratifié VAT, Optimisation, Flambage, NURBS, matériaux composites
Keywords : VAT laminates, Optimisation, Buckling, NURBS, composite materials

1. 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 [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. 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 [3]. 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 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. 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 [4], [5] to the case of VAT composites [9], [10]. 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.

2. 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 [6].
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 [7], [8];
- 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.

3. 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 [9], [10] show that it is possible to obtain an optimum solution meeting all the imposed requirements and having a buckling load 67% higher that of a standard aeronautical stacking sequence (straight fibres).

References

[1] Z. Gurdal, B.F. Tatting, K.C. Wu, Variable stiffness panels: Effects of stiffness variation on the in -plane and buckling responses, Composites Part A: Applied Science and Manufacturing, 39(9), 2008, 11-22.

[2] A. Catapano, Stiffness and Strength Optimisation of the Anisotropy Distribution for Laminated Structures, PhD Thesis, UPMC Paris 6, 2013.

[3] M.A. Nik, K. Fayazbakhsh, D. Pasini, L. Lessard, Surrogate-based multi-objective optimization of a composite laminate with curvilinear fibers, Composite Structures, 94, 2012, 2306-2313.

[4] M. Montemurro, A. Vincenti, P. Vannucci, A two-level procedure for the global optimum design of composite modular structures - application to the design of an aircraft wing. Part 1: theoretical formulation, Journal of Optimization Theory and Applications, 155(1), 2012, 1-23.

[5] M. Montemurro, A. Catapano, D. Doroszewski, A multi-scale approach for the simultaneous shape and material optimisation of sandwich panels with cellular core, Composites Part B: Engineering, 91, 2016, 458-472.

[6] G. Verchery, Les invariants des tenseurs d'ordre 4 du type de l'élasticité, Proc. of colloque Euromech 115, VIllard-de-Lans, F, 1979.

[7] M. Montemurro, An extension of the polar method to the First-order Shear Deformation Theory of laminates, Composite Structures, 127, 2015, 328-339.

[8] Montemurro M. Corrigendum to an extension of the polar method to the first-order shear deformation theory of laminates [Compos. Struct. 127 (2015) 328–339]. Composite Structures; 13, 2015, 1143–4.

[9] M. Montemurro, A. Catapano. Chapter: A new paradigm for the optimum design of variable angle tow laminates. In: Variational analysis and aerospace engineering: mathematical challenges for the aerospace of the future. Springer optimization and its applications, 1st Ed. vol. 116. Springer International Publishing; 2016. http://dx.doi.org/10.1007/978-3-319-45680-5.

[10] M. Montemurro, A. Catapano, On the effective integration of manufacturability constraints within the multi-scale methodology for designing variable angle-tow laminates, Composite Structures, 161, 2017, 145-159.