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Multiscale topology optimization of bi-material laminated composite structures

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ABSTRACT

This work describes a computational model to design bi-material composite laminates, with the objective of optimally design the structure and its material, using a multiscale topology optimization model. It assumes two scales dealing with the structural and the material levels respectively, both for analysis and design.

The model is based on a hierarchical structural optimization strategy that takes into account the manufacturing process and fundamental characteristics of composite laminates to minimize the structural compliance. It assumes a mixed set of micro and macro design variables to characterize the distribution of two materials and obtain the optimal composite microstructure at the micro design level and the optimal fiber orientation at the macro level. The results obtained demonstrate that multiscale topology optimization, applied to laminated composite structures, opens the possibility for improved and innovative designs when compared with classical laminated composite design solutions. In addition, these results are helpful to gain insight into the effectiveness of the microstructure features of composite laminates.

1. Introduction

In this work we address the problem of optimally design bi-material fiber composite laminates for structural compliance minimization. Besides fiber orientation, we assume that the composite microstructure is also designable, and the goal is to characterize the material unit cell topology defining the two materials distribution.

In topology optimization of structures, the design of bi-material structures has been initially formulated as a two materials distribution problem only at the macro or structural level, see e.g. [1]. The present design model increases the design possibilities formulating a multi-scale design problem to find each material distribution at the micro (material) scale, see e.g. [2]. Recently multi-scale design of material and structure has seen a strong progress with the use of optimization methods, namely topology optimization based methodologies. The works in [2–15] describe some of these recent developments.

To formulate and solve the multiscale optimal design problem, we follow a hierarchical approach, as described in [16]. Thus, one considers two scales (macro and micro-scales) identified with the design domains of the structure and its material, respectively. The class of composite materials is restricted to periodic materials, with the material unit cell topology locally optimized for the given objective function and constraints.

With the objective of optimizing laminated composite structures, we define a design space that includes material directionality (fiber orientation) at the macro level and an optimal choice of materials and respective volume fractions at the micro level (fiber and matrix phases topology design). Based on the laminate intrinsic geometry the design is assumed uniform in each lamina. Thus the macro design variable characterizing fiber orientation is constant in each lamina, see e.g. [17–20], as is the case for the bi-material (fiber – matrix) optimal distribution characterized by a material micro-density variable. The micro material density distribution characterizes the material microstructure topology (fiber versus matrix) at the material unit cell level and a macro density, sets the percentage of fiber versus matrix, at the lamina level. This design methodology is more restrictive, in terms of design efficiency, when compared to the approach presented in [13]. However, is less restrictive than common design approaches for laminates that assume for example integer optimization for ply angles and stacking sequences, with prescribed composite fiber microstructures, see e.g. [21].

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In this work, optimal composite laminates are identified for minimum compliance with a global material resource constraint that imposes an upper limit on the total amount of fiber. The results obtained demonstrate that hierarchical topology optimization applied to laminated composite structures identifies improved and innovative designs, when compared with classical laminated composite solutions. In addition, these results are helpful to gain insight into the effectiveness of the microstructure features of composite laminates when subjected to different loading conditions [22].

2. Hierarchical material model

The hierarchical material design model described here, for bi-material laminate composite optimization, is outlined in Fig. 1. A laminated plate with *N* layers (plies) mixes two materials (e.g. *E*-glass and Epoxy). Each ply or lamina is a composite material, and all are assumed perfectly bonded, so displacements will be continuous across the laminate thickness. Consequently, inter-laminar effects such as delamination are disregarded here.

As in [13], a design domain Ω is defined for the macroscale, or structural level, where the goal is to find an optimal structure lay-out for given loads and support conditions. Also a design domain Y is defined for the microscale, or material level, where the aim is to find the optimal design of the composite material unit cell (periodic material is assumed).

Rodrigues et al. in [16] considered that each (macro) point $\mathbf{x}$ in Ω is designable, *i.e.* a relative density design variable ρ and a material unit cell geometry, described by the micro density field $\mu(\mathbf{x},\mathbf{y})$, is defined at each $\mathbf{x}$. Here the designable part of the macroscopic domain is subdivided into "larger" areas (design subdomains Ω_i, see e.g. [2]). In each subdomain the designed material is uniform at the macro level – patch design concept – (see *e.g.* [17,19,20]) and these designable sub-domains are identified with the plies (lamina) of the composite laminate. Therefore the optimal design problem is formulated as a two scale material distribution problem (macro and micro), and a "density" field, assumed constant within each lamina, governs each one, $\rho(\mathbf{x})$ and $\mu(\mathbf{x},\mathbf{y})$, respectively. So one has as many micro (local) problems as the number of laminas.

Following the description in Fig. 1a, the plane of each ply is parallel to the global Ox_1x_2 reference plane. All the laminate plies are of equal thickness and the x_3 direction is normal to the laminate. The local coordinate system $Oy_1y_2y_3$ is associated to the unit cell reference domain Y, see Fig. 1b. This domain is a square where the optimal fiber cross-section topology is to be defined. It is on the Oy_2y_3 plane and thus y_1 identifies the fiber direction. Local and global reference frames differ by the fiber rotation angle. This rotation is defined in the reference system $Oy_1y_2y_3$ using the angle θ around the plate normal axis $x_3 \equiv y_3$, see Fig. 1.

The material model used for microstructure design comprises two materials mixed to form a fiber/resin compound for each lamina and thus get a continuum structure composed of two distinct, linearly elastic materials. The goal is to determine the optimal cross-section topology of the stiffer (fiber) material within the weaker (matrix) material (see Fig. 1b). The relative density macro design variable ρ_i defines the volume fraction for the fiber phase in the *i*th lamina. The volume fraction for the resin phase is then given by 1-ρ_i. The resource bound $\overline{V}$ limits the total amount of stiffer material (fiber) used in the structure. It is assumed that the macro and micro scales differ by a proper size ratio, *i.e.* the material unit cell characteristic size *d*, is much smaller than the global domain characteristic size *D* [23].

3. Computational structural analysis model

The numerical model uses a finite element approximation to solve the structural (macro) and the material (micro) analysis problems. For the macro problem, the structural domain is discretized using $n \times n$ 4-node elements SHELL181 (from ANSYS@) with six degrees of freedom (*d.o.f.*) and multilayer capability as exemplified in Fig. 2(left). A detailed three-dimensional (solid) modeling of the multilayered composite plate using hexahedral

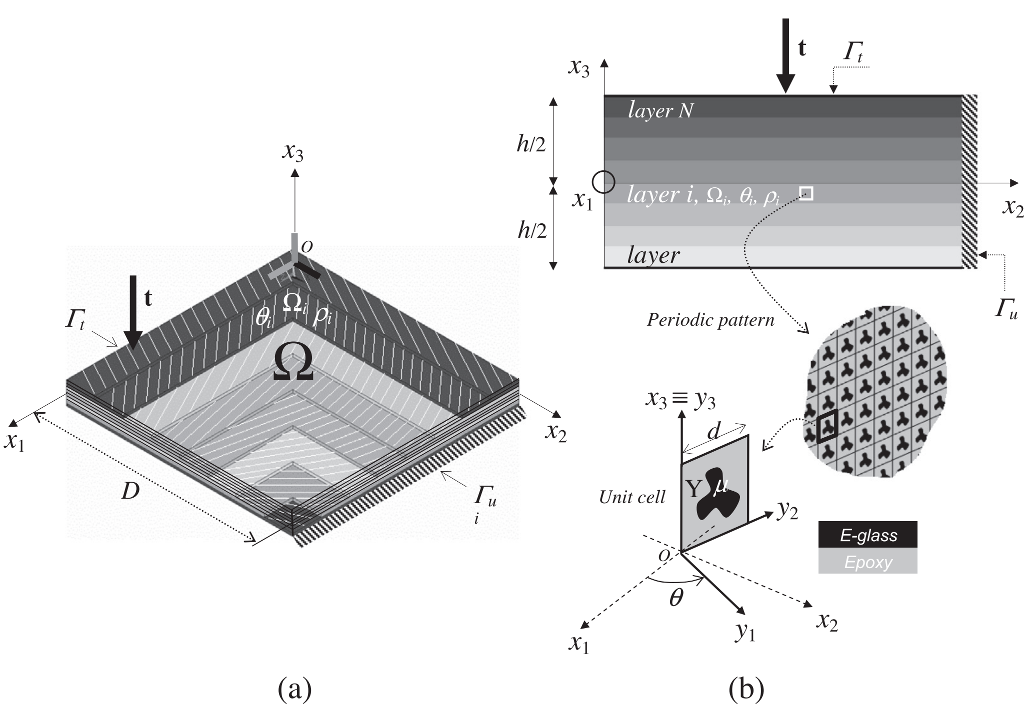

Fig. 1. Hierarchical design model for laminated composite structures with *N* layers. (a) Global $Ox_1x_2x_3$ and (b) local $Oy_1y_2y_3$ coordinate systems and material directionality θ are shown.