



A multi-scale approach for the simultaneous shape and material optimisation of sandwich panels with cellular core



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ABSTRACT

This work deals with the problem of the optimum design of a sandwich panel made of carbon-epoxy skins and a metallic cellular core. The proposed design strategy is a multi-scale numerical optimisation procedure that does not make use of any simplifying hypothesis to obtain a true global optimum configuration of the system. To face the design of the sandwich structure at both meso and macro scales, a two-level optimisation strategy is employed: at the first level the goal is the determination of the optimum shape of the unit cell of the core (meso-scale) together with the material and geometric parameters of the laminated skins (macro-scale), while at the second level the objective is the design of the skins stacking sequence (skin meso-scale) meeting the geometrical and material parameters provided by the first-level problem. The two-level strategy is founded on the polar formalism for the description of the anisotropic behaviour of the laminates, on the NURBS basis functions for representing the shape of the unit cell and on the use of a genetic algorithm as optimisation tool to perform the solution search. To prove its effectiveness, the multi-scale strategy is applied to the least-weight design of a sandwich plate subject to constraints of different nature: on the positive-definiteness of the stiffness tensor of the core, on the admissible material properties of the laminated faces, on the local buckling load of the unit cell, on the global buckling load of the panel and geometrical as well as manufacturability constraints related to the fabrication process of the cellular core.

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1. Introduction

Sandwich panels are increasingly used in aerospace, automotive and naval industries thanks to their high stiffness-to-weight and strength-to-weight ratios. In order to further reduce the weight of these structures, sandwich panels are made by laminated skins separated by aluminium or resin honeycombs, or by polymer foams whose material and geometrical properties can be designed to provide sandwich plates with enhanced mechanical properties (stiffness, strength, etc.). However, the design process and the subsequent optimisation of sandwich structures presents several difficulties mainly when the panel is made of laminated skins and a honeycomb core. In this case the designer has to face, into the same design process, both the difficulty of designing a laminated plate

(concerning the skins) and that of designing a complex 3D cellular continuum such as the honeycomb core. Therefore, engineers always make use of some simplifying assumptions or rules to obtain, in an easy and fast way, a solution. For example, in Refs. [1–3] the optimal design of a sandwich plate is addressed by determining exclusively the optimum thickness of both the core and the skins, keeping constant the rest of geometric and material parameters of the system. In Ref. [4] the authors deal with the problem of the least-weight design of a sandwich plate considering as design variables the thickness of the cell walls as well as that of the skins together with the total height of the panel. They employed an analytical model to evaluate both the buckling load of the core and the faces yielding which were considered as optimisation constraints. The optimisation problem was solved using a Genetic Algorithm (GA). A step further in the formulation of the problem of the optimum design of sandwich structures has been done by introducing the concept of topology optimisation of periodic structures. For example, in Ref. [5] Neves et al. present two computational models for predicting the topology of periodic

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microstructures which optimise the equivalent material properties determined through a numerical homogenisation technique. Barbarosie and Toader [6] derive analytically the shape and topological derivatives for elliptic problems in unbounded domains subject to periodicity conditions. In Ref. [7] Wadley et al. compare different topologies of sandwich cores in order to evaluate their structural performance along with the most suited fabrication process. In this work the classical configurations of sandwich cores such as foams or honeycombs are questioned and the authors show how new shapes of the repetitive unit cell, obtained through an optimisation process, can lead to more efficient solutions (i.e. lighter and stiffer). In Ref. [8] Huang and Xie present a method for the topology optimisation of periodic structures using the bi-directional evolutionary structural optimisation technique. The capability and the effectiveness of their approach is demonstrated through some numerical applications on sandwich structures.

The study presented in this work can be placed within the framework of the research activities [9,10] previously conducted by the authors and can be seen as a generalisation of these works.

In Refs. [9,10] a very general multi-scale procedure for the optimum design of sandwich panels with a hexagonal honeycomb core is proposed. The design problem is formulated without introducing simplifying hypotheses and by considering (as design variables) the full set of geometric and material parameters defining the behaviour of the structure at each characteristic scale (meso and macro). The design variables are the geometric parameters of the hexagonal unit cell (meso-scale) together with the geometric and material parameters of the laminated skins (meso and macro scales). To deal with the multi-scale design problem of a sandwich plate a two-level optimisation strategy is employed. At the first level of the procedure the optimum value of the cell parameters along with the material and geometrical properties of the laminated skins are determined (at this level each skin is modelled as an equivalent homogeneous anisotropic plate whose mechanical behaviour at the macro-scale is described through a set of tensor invariants, i.e. the laminate polar parameters [11]). At the second level of the strategy the goal is to find at least one stack for each skin (thus the design variables of this phase are the plies orientation angles) meeting the optimum combination of their material and geometrical parameters resulting from the first level of the procedure.

The aim of the present work is twofold. On one hand the formulation of the design problem of the sandwich panel is generalised by considering the shape optimisation of the unit cell of the core instead of the classical size optimisation of a prescribed geometry (as done in Refs. [9,10] for the hexagonal unit cell). On the other hand the two-level optimisation procedure has been enriched by considering the manufacturability constraints linked to the fabrication process of the unit cell within the first level of the strategy. In order to fabricate in an easy and fast way a prototype of the cellular core a 3D printing technique has been considered as a fabrication process. Concerning the geometry of the cellular core, the shape of the unit cell is described by means of B-spline and Non-Uniform Rational B-Spline (NURBS) curves [12]. The utilisation of B-spline and NURBS bases allows for easily translating the manufacturability constraints (due to the additive manufacturing process) into geometrical constraints to be imposed on the geometry of the representative unit cell. Moreover, since the first level of the strategy involves two different scales (the macro-scale of the sandwich panel and the meso-scale of the cellular core) the meso-scale 3D finite element model of the repetitive unit cell of the core presented in Ref. [9] (which is used to evaluate its effective elastic properties at the macro-scale) has been generalised in order to take into account for the variation of the shape of the cell. The whole procedure is based on the utilisation of the polar formalism [13] as

well as on a genetic algorithm (GA) previously developed by the first author [14]. The paper is organised as follows: the design problem, the two-level strategy and the rapid prototyping technique used for fabricating the cellular core are discussed in Section 2. The mathematical formulation of the first-level problem is detailed in Section 3, while the problem of determining a suitable laminate is formulated in Section 4. A concise description of the Finite Element (FE) models of the sandwich structure at both meso and macro scales is given in Section 5, while the numerical results of the optimisation procedure are shown in Section 6. Finally, Section 7 ends the paper with some concluding remarks.

2. Simultaneous shape and material optimisation of sandwich panels with cellular core

2.1. Description of the problem

The optimisation strategy presented in this study is applied to a sandwich plate composed of two laminated skins and a metallic cellular core with *free-shape* cells as depicted in Figs. 1 and 2. The skins are made of carbon-epoxy unidirectional orthotropic laminae while the cellular core is obtained from aluminium alloy foils, see Table 1 for the material properties taken from Refs. [15,16]. Concerning the cellular core, its elastic response together with its effective material properties (at the macro-scale) are determined under the following assumptions:

- linear, elastic behaviour for the material of the cell walls;
- perfect bonding for the wall-to-wall contact;
- the buckling of the cell walls due to shear stresses is disregarded.

Concerning the mechanical behaviour (at the macro-scale) of the identical laminated skins, they are modelled as quasi-homogeneous fully orthotropic laminates, see Section 3.2. As discussed in Ref. [10], no simplifying hypotheses are made on the geometric and mechanical parameters of both skins and core. Only avoiding the utilisation of a priori assumptions that extremely shrink the solution space (e.g. the utilisation of symmetric balanced stacks for the laminated faces to attain membrane/bending uncoupling and membrane orthotropy, respectively, or the utilisation of regular hexagonal cells to reduce the number of optimisation variables for the core) one can hope to obtain the true global optimum for a given problem: this is a key-point in our approach.

Finally, in this work the problem formulation has been enriched by including the shape optimisation of the unit cell of the cellular core (which is not fixed a priori) as well as the manufacturability

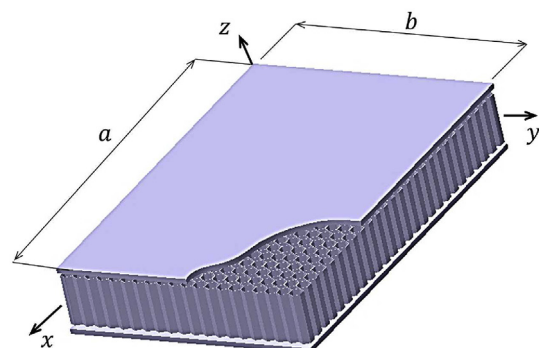


Fig. 1. Geometry of the sandwich panel.

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