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A new design paradigm for the analysis and optimisation of composite structures.

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This work is articulated in three parts. Firstly, the Verchery's polar method [1, 2] (a mathematical representation of the plane anisotropy based upon tensor invariants) is extended to the theoretical framework of both the First-order Shear Deformation Theory (FSDT) [3] and the Third-order Shear Deformation Theory (TSDT) [4] of laminates. Concerning the polar analysis of the FSDT, the major analytical result is that the number of independent tensor invariants characterising the laminate constitutive behaviour remains unchanged when passing from the context of the Classical Laminate Theory (CLT) to that of the FSDT. On the other hand, the major analytical results of the application of the polar formalism to the TSDT of laminates are the generalisation of the concept of a *quasi-homogeneous laminate* as well as the definition of some new classes of laminates. Moreover, for both theories, it is proved that the elastic symmetries of the laminate shear stiffness matrices (basic and higher-order terms) depend upon those of their in-plane counterparts.

Secondly, a new design paradigm for the analysis and optimisation of composite structures consisting in a multi-scale numerical optimisation procedure that relies on the polar formalism and on the use of a special evolutionary algorithm is proposed. In particular, given a hybrid structure to be designed (according to some prescribed requirements), the proposed strategy is articulated into two distinct (but linked) problems as described here below.

1. *First-level problem.* The aim of this phase is the determination of the optimum shape and 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 each laminate composing the hybrid structure is modelled as an equivalent homogeneous anisotropic continuum whose behaviour at the macro-scale is described in terms of laminate polar parameters, see [3-9]. This level can also involve different scales (typically meso and macro scales) thus the problem must be formulated and solved by considering the full set of design variables intervening at each scale [5-7]. Of course, when different scales are involved within the first-level problem a homogenisation phase (numerical or analytical) of the structure must be considered in order to determine the effective

material properties of some parts of the structure that will be used at the macro-scale (which depend upon the geometric/material parameters characterising the lower scale).

2. *Second-level problem.* At the second level of the strategy, the goal is the determination of the optimum lay-up of the laminates composing the structure (the laminate meso-scale) meeting the optimum combination of their material and geometrical parameters provided by the first level of the strategy. At this stage, the design variables are the layer orientations and the designer can add some additional requirements, e.g. more constraints on the elastic behaviour of the laminate or the orientations of the layers can be restricted to a set of possible values, etc.

For a deeper insight in the matter (especially concerning the mathematical formulation underlying the multi-scale two-level optimisation strategy) the reader is addressed to [5-6, 8-9].

Finally, the effectiveness of this strategy is proved through the resolution of a real-world engineering design problem: the least-weight (multi-scale) design of a sandwich panel composed of CFRP faces and Al honeycomb core. The goal here consists in simultaneously optimising the shape of the unit cell (meso-scale) of the honeycomb core (which will be fabricated by means of an additive manufacturing technique) and the geometrical as well as the material parameters of the CFRP laminated skins (meso and macro scales). This design problem is formulated as an optimisation problem subject to constraints of different nature [5-7]: 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 of the core, on the global buckling load of the panel and geometrical as well as manufacturability constraints linked to the fabrication process of the honeycomb core.

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