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Structural efficiency metrics for integrated selection of layup, material, and cross-section shape in laminated composite structures

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Previously introduced to assess the structural efficiency and to ease the selection of solid materials and cross-section shapes, the method of shape transformers is here extended to deal with the structural design of laminated composites. In particular, this work examines laminated composites under bending and torsional loading, and considers as free variables of selection the layup, the number of plies, the shape of the cross-section, and the materials that make up a laminated structure. Structural efficiency measures are first formulated to assess the merit of selecting each of these variables separately, and later applied to generate design charts that enable their concurrent selection. The results visualized in maps help identify in a glance the role that each of the variables plays in the structural efficiency of a laminated composite structure, as well as assist in the choice of the best laminated composite concept at the preliminary stage of design.

1. Introduction

With the recent advent of automated processes for composite manufacturing, the use of laminated composites is steadily increasing and stretching its potential with applications stemming from a large spectrum of sectors, including aerospace, marine, and land. In general, fiber orientations, stacking sequence, and laminate thickness are some, among several others, design variables that can be rationally optimized to obtain laminated structures with excellent mechanical properties at minimum mass.

The design of a single laminate is generally less challenging than the design of a structure, like a cantilever, made of composite laminates. In this case, besides the stacking sequence, other design variables, such as the cross-section shape and the overall form of the structure, can be chosen as design variables to achieve a performance improvement. In a composite laminated structure with constant stiffness, variables governing its specific stiffness and strength include the fiber orientation in each layer, the layup, the constituent materials of each layer as well as the cross-sectional shape of the structure. Since some of the material-related variables are directional and their interaction with the structural variables can be strong, the structural design of laminate composites can often present higher complexity than that with conventional materials. Thence, design tools of selection can be handy at the concept stage of design as they can assist in making educated choices on the design variables that can best maximize structural efficiency in a given application.

A number of approaches have been proposed for material and shape selection of monolithic or hybrid materials [1–3]. One of the most popular is the pioneering method of Ashby, which was first introduced for the selection of monolithic shaped materials via performance indices, and then it was extended to hybrid materials [4–6], with fibrous composites being an example [7]. More recently, in the context of composite materials, Buckney et al. [8] presented shape factors to measure the structural efficiency of beam cross-sections under asymmetric bending, and applied them to a cross-section composed of multiple materials. Another work that provides metrics for ranking alternative design configurations for composites is that of Thomas and Qidwai [9], who used material-architecture indices to quantitatively correlate system-level performance of discrete composite components to that of their constituent properties describing material and geometry. While effective in providing design tools of selection for multiple material components, the works above do not examine the layup of a composite laminate and thus are of limited use in the choice of the layup for a laminated composite structure.

With respect to the layup design of a laminate composite, tools for layup selection exist and carpet plots are one example [10]. Carpet plots allow to find an appropriate laminate layup for given

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load conditions and mechanical requirements. Carpet plots illustrate how a given laminate property depends on the percentage of plies at each orientation. Carpet plots are handy to use and can thus offer a convenient tool for the early stage selection of the laminate layup. Later, such plots were used and extended by Weaver [11] in a work for layup selections of composite structures, where a database of laminate layup was developed to store the properties of all permutations of layup angles. A series of maps presented to search a subset of laminates that perform well on each chart, allows to visually identify trends of properties that might otherwise be overlooked by using numeric methods. Building upon Weaver's methodology [11], more recently Monroy Aceves et al. [12] combined the use of FE analysis with the selection software CES [13] to help designers select a shortlist of composite structures from a large number of options. These charts give freedom to modify the selection criteria and design requirements to allow interactive selection of data. The methodology was also applied to a real case study, requiring the design of a small low-speed composite wind turbine blade [14], showing its suitability in identifying the most promising concept for a composite blade. Whereas the works mentioned above focus on the layup and/or material selection in shell or plates made of composite materials, the interaction between cross-section shape, material and layup in laminated composite selection has not been examined yet and it is thus the focus of this paper.

In this work, we extend a method previously introduced for material and shape selection of lightweight structures [15–18]. It is based on the definition of shape transformers, dimensionless measures that can be defined for any geometric properties of a structure, such as its volume. Shape transformers describe shape properties regardless of size and material, and are thus invariant to any scaling imposed to the size of a structure. The method allows to distinctly capture the role of cross-section shape and material in the structural properties and structural efficiency of a structure. Previously used for the co-selection of shaped materials in single and multi-objective applications [15–18], the method is here extended to integrate information on the layup, making it capable of handling the design and selection of laminated composite structures. In Section 2, the paper starts by reviewing the fundamentals of the method before focusing on extending the formulation to obtain performance indices for laminated composite beams. In Section 3, the developed indices are used to generate selection charts showing the role of cross-section shapes, material properties and layup in bending and torsional stiffness design. Selection charts for bending and torsional strength design are also presented in Section 4, which is followed by concluding remarks.

2. Methodology

2.1. A brief review of the concept of shape transformers

Introduced for solid materials and applied to problems of selection for lightweight design [19], vibration [15], and biological beams [20], shape transformers have been formulated for a range of loading scenarios including stiffness and strength in pure bending [16,21], torsion stiffness [18], and combination of bending and shear [17].

For a given prismatic structure, such as that shown in Fig. 1, we can conveniently assume the structural properties to be dependent on the material (M) it is made of, the shape (S) of its cross-section, and the overall size, here conveniently described by the rectangular envelope (D) with dimensions (H), (B) and (L). As material properties allow comparing materials for a given envelope D, similarly we can define shape properties, namely shape transformers, that are normalized with those of the envelope and are thus dimensionless. Shape transformers can be defined for the area, volume, second moment of area and other given geometric quantities (G) of a structure, so as to be invariant to scaling. For a given cross-section, a shape transformer (Ψ_G) of a geometric quantity G is defined by normalizing the geometric quantity G by the same geometric quantity of its envelope G_D, such that $\Psi_G = G/G_D$. For example, $\Psi_A = A/A_D$ is the shape transformer of area, where A is the area of the cross-section and A_D is the area of the envelope.

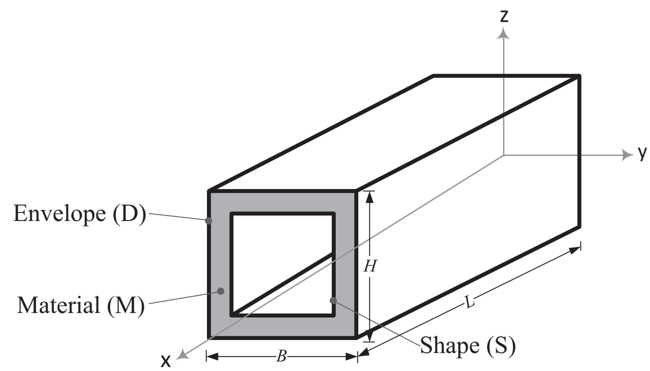

Fig. 1. Hollow prismatic beam made of a uniform homogenous material with its design variables (M, S, D).

Table 1 shows a summary of the performance indices containing shape transformers that were formulated to measure the structural efficiency of a cross-section in stiffness and strength designs under bending and torsional loadings. On the upper part there are indices for solid materials [15–18], whereas in the lower part are those that are derived in the next section of this work for laminated composites.

2.2. Extension of the definition of shape transformers to laminated composites

Whereas Fig. 1 shows a prismatic beam of solid materials, Fig. 2 shows its counterpart beam made of composite laminates, the object of our study. Variables we focus here our attention on, are (M, S, θ, n), where M is the material of each ply, S the cross-section shape, θ and n the ply angle of each layer and the number of plies. The size of the structure, namely the envelope D, is prescribed. With convention following the right-hand-rule, the x-axis is the beam axis and the beam cross-section is in the y-z plane. In this work we examine the stiffness in the z-direction. Further work is required to generalize the analysis to other directions.

Whereas for solid materials the role of material and shape could be conveniently decoupled in the formulation of the performance indices [15–18], for laminated composites there exists a intrinsic interaction between material, shape, and layup, variables that are thus are difficult to decouple, as seen from the formulations derived in [22]. For this reason, the performance indices for laminated composites are here defined for stiffness and strength design as a bending index (Ψ_{EI}) which is the ratio of bending stiffness of a candidate cross-section normalized to the reference cross-section. For the reference cross-section, the beam is made of composite materials, and its cross-section shape, number of plies and ply angle for each layer can be specified according to the design references and requirements. In this work, as later described in Section 3, we refer to a reference cross-section with square box shape, 16 plies and 0° degree of angle for all layers made of E-Carbon Epoxy (CFRP). With this information on the reference cross-section, we can define the bending stiffness index as

$$\Psi_{EI} = \frac{EI}{(EI)_0} \tag{1}$$