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Maturity assessment of the laminate variable stiffness design process

Anthony Sabido, Luis Bahamonde, Ramy Harik [*,1], Michel J.L. van Tooren

University of South Carolina, Columbia, SC, 29201, United States

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ABSTRACT

Variable stiffness (VS) laminate design methods allow to tailor the composite to a particular problem. This enlarged design space exploration is assisted by optimization algorithms and physics-based analyses. Although, the applicability of this methodology is at very early stages the search algorithms and analyses have evolved into sophisticated solutions. This survey aims to review the maturity of such models. However, a holistic approach must be formulated to account for all development activities like analysis, manufacturing, and certification. This survey classifies and reviews VS design papers over three decades of VS design methods to assess VS design maturity. Each paper is classified based on the research design criteria. We find that VS has evolved from a concept formulated in the early 1990s, proven through numerous feasibility studies that considered multiple performance criteria, mostly implemented into research-grade automated design tools considering fiber steering as the VS enabling mechanism, and extended into holistic-oriented multi-step design frameworks that incorporate efficient optimization algorithms, manufacturability and multidisciplinary analyses. However, certifiability considerations and more realistic structural representations have been found lacking in these frameworks. The latter is currently being researched, however the former has seen no investigative thrust.

Contents

1. Introduction

Variable stiffness (VS) laminates are advanced composite concepts where the material stiffness is modeled as a spatially distributed property and tailored to specific loading conditions. These gains in structural performance are usually traded, in the

* Corresponding author.
E-mail address: harik@cec.sc.edu (R. Harik).
[1] Assistant Professor, USC/McNAIR Center for Aerospace Innovation and Research.

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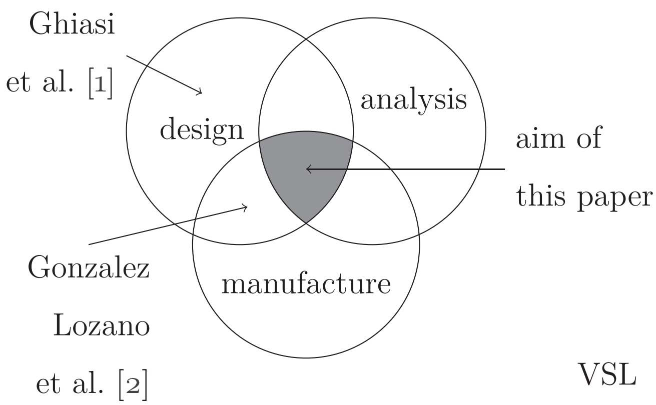

Fig. 1. variable stiffness laminates literature reviews.

design stage, against structural efficiency or manufacturability. Thus, VS laminate design accounts for the whole development lifecycle, from analysis to design to manufacturing. Many papers have made great strides addressing these three capabilities independently during the almost three-decade-long history of this methodology. Moreover, several comprehensive review papers have focused on each independent capability. Ghiasi et al. [1] review the optimization methods used in VS design. Gonzalez Lozano et al. [2] review the manufacturability of VS designs. Finally, Ribeiro et al. [3] focus on the mechanical behavior of fiber steered designs. Fig. 1 illustrates with a Venn diagram the focus of each review paper within the VS literature. One can see from Fig. 1 that the intersection of analysis, design, and manufacture represents all the phases of composite development. Thus, it can be understood as representing holistic design methodologies that account for manufacturing and different analyses. It is the main aim of this review paper to systematically classify VS design research accounting for manufacturability, analytical models, and design procedures. The motivation of this work is to study the evolution of VS design and identify the maturity stage of the mathematical representations used for VS design.

The wholesome of a design methodology will be evaluated based on multicriteria structural performance, manufacturing considerations and analysis fidelity. As a secondary goal we aim to update Ghiasi et al. [1] review on VS design accounting for the last six years. The manufacturing methods for which design is considered are fiber placement and continuous tow shearing (CTS).

Variation in the material properties as a function of location can be achieved with four structural design concepts. First, one can steer the fibers of a given ply to form curvilinear paths. Second, the fiber volume fraction can be a function of location. Third, the thickness of each ply can have a spatial distribution. Finally, a discrete approach can be taken for each one of the last three concepts and yield a patched design.

Most VS design papers are problem dependent. As such, The paper is structured as follows. A design problem is classified based on the design criteria: stiffness (Section 2), strength (Section 3), dynamic performance (Section 4), buckling (Section 5), postbuckling (Section 6), and thermal performance (Section 7). Multi-objective problems or design cases that consider several structural performance criteria are classified in Section 8. Furthermore, in our opinion weight minimization problems simply trade performance improvements for structural efficiency and as such the problem is classified under the performance criteria it is traded with. Section 9 discusses the classified papers and draws conclusions on the maturity of VS design.

2. Design for stiffness

Structural stiffness is a global and abstract notion [4]. As such, several structural quantities can be used to maximize stiffness. Elastic strain energy [5–10] or global forces [11] are two amongst them. Nonetheless, the literature has equivalent reformulated local problems. The approach is based on an optimality criterion formulation for the minimum compliance problem [5,8]. Table 1 shows stiffness-based design problems chronologically ordered and labeled according to the optimality criteria used.

In terms of design strategies, Hammer et al. [5] are the first authors to perform a VS laminate optimization based on the lamination parameters (LP) approach. The main argument for using LP as design variables is the small number of parameters and the linear dependence of the compliance with LP, which creates a convex design space. Setoodeh et al. [9] also study the minimum compliance problem for both LP and direct fiber orientation angle parametrizations. They find that LP designs are significantly superior than the direct fiber angle parametrization. However, the former requires a post-processing step to retrieve the fiber paths. This post-processing step is presented by Setoodeh et al. [12] using curve fitting techniques, albeit, the approximate design yields less performance enhancements than the theoretical bounds set by the LP optimization. Conversely, taking advantage of the local optimality criteria that can be derived from the minimum compliance problem, Setoodeh et al. [7] present a cellular automata method to simultaneously analyze and design each local cell. Several design case studies are solved to prove the robustness of the algorithm. Next, Setoodeh et al. [8] implement a heuristic pattern-matching technique to maintain fiber orientation continuity for manufacturability purposes. In regards to manufacturability considerations, Langley [11] presents a finite element (FE) model that accounts for manufacturing limitations such as tow width and overlaps.

Finally, design speed is also adressed by Duvaut et al. [6] who use a variational formulation to develop an algorithm they show to be convergent and fast.

3. Design for strength

As stated by Khani et al. [13], it was a common belief that design for stiffness could serve as a surrogate for strength. Table 2 summarizes research papers that have studied problems where it is very important to consider strength as a design criteria. Most typical examples of strength optimization using VS laminate concepts study a plate with a cut-out that introduces stress concentrations (see Table 3 and Table 5).

Table 2 also shows that many test trials where performed before the year 2000. In that timeframe most research was focused towards aligning the fibers with the stress trajectories, with the purpose of minimizing the shear stress. Tosh and Kelly [22] experimentally study different failure criteria for fiber steerings. On the other hand, Crothers et al. [19] use a finite-element-based optimization method called computer aided internal optimisation to design the fiber orientation architecture for a strength-constrained weight minimization. They validate their results with experimental tests.

In the last fifteen years, higher fidelity analysis including detailed failure criteria models have used less experimental testing in their research studies. It can be seen from Table 2 that the most frequently used failure criteria is the Tsai–Wu criterion followed by Tsai–Hill. Crucial to strength optimization, is Groenwold and Haftka's [31] proof that minimizing the failure criteria, is not necessarily conductive to maximizing the failure load when the failure criteria is non–homogeneous. Instead the authors propose using a safety factor as the objective function. This approach is used by

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