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Exploring how optimal composite design is influenced by model fidelity and multiple objectives

Shreyas Joglekar, Kayla Von Hagel, Mark Pankow, Scott Ferguson *

Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695, USA

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ABSTRACT

This paper explores how optimal configuration of a composite panel is influenced by the choice of analysis model – analytic or computational – and the consideration of multiple objectives. While past research has explored aspects of this problem separately – composite ply orientation, multiple load scenarios, and multiple performance objectives – there has been limited work addressing the interactions between these factors. Three loading scenarios are considered in this work, and it is demonstrated that for certain scenarios an analytical model likely over-predicts composite performance. Further, for complex loading scenarios it is impossible to develop an analytical model. However, this work also demonstrates that the use of analytical models can be advantageous. Analytical models can provide similar estimates to computational models for some loading cases at significantly reduced computational expense. More importantly, it is also shown how solutions from the analytical model, which can be relatively cheap to find computationally, can be used to seed the initial designs of a Finite Element-based optimization. Run time reductions as large as 80% are demonstrated when these informed seeded designs are used, even when the designs were created for a different set of loading scenarios.

1. Introduction

Composite laminate design problems often involve large design spaces that are discrete or mixed-integer. Engineers control the number of layers and tailor the stacking sequence and fiber orientation to the load path of a structure [1–3]. Additionally, choices have to be made between (1) incorporating time-saving, low-fidelity models or (2) accepting the computational cost and/or risk of missing a deadline by using high-fidelity models. After the problem is formulated and the analysis model is chosen, an optimization is completed and the solutions are used to guide composite design decisions [4–8].

Early researchers formulated single objective optimization problems with reduced design spaces and used analytical models to diminish computational cost. Improved computational resources have led to a greater prevalence of computational models that are more complex and the consideration of larger design spaces that require advanced optimization techniques. The presence of multiple loading scenarios further complicates the selection of an optimal configuration. An optimal composite layup for a single loading scenario is likely to be drastically sub-optimal across multiple loading scenarios. The need to navigate such trade-offs is common, especially in aerospace engineering applications where composites may experience uniaxial tension and transverse compression, uniaxial tension and biaxial compression, and load cases with out-of-plane pressure.

Yet little, if any, research exists that explores problems with multiple load scenarios and competing performance objectives. In light of more complete theoretical [9–11] and computational models [2,12] that have been created from increased understanding of composite panel design, a better understanding of the relationship between model selection, computational cost, and quality of solution is needed.

The objective of this paper is to explore the differences in optimal composite configuration when a choice is made between using an analytical model or a computational Finite Element (FE) model in the presence of multiple performance objectives across three different loading conditions. The research presented in this paper compares where analytical and computational models exhibit similar and different solution behavior. This outcome is important because it directly addresses the challenge of when each model can be used to facilitate exploration (generating new design candidates and analyzing them cheaply) versus where exploitation may

* Corresponding author.
E-mail addresses: ssjoglek@ncsu.edu (S. Joglekar), kavonhag@ncsu.edu (K. Von Hagel), mrpankow@ncsu.edu (M. Pankow), scott_ferguson@ncsu.edu (S. Ferguson).

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be needed using more computationally expensive models to ensure the estimated performance of a design is accurate.

Previous research has considered multiple objectives for a single load case when continuous angle orientations are used [13–15]. Conversely, computational cost is managed in research that considers multiple load cases by restricting the number of possible orientation angles (typically to 5 or less) and relying on single objective formulations [16]. This paper extends existing efforts by allowing each ply to take on one of 19 possible fiber orientations and by formulating multi-objective problem formulations for each of the three loading scenarios considered. Outcomes from each model are then analyzed for differences in terms of estimated system performance and the design configurations that comprise the final solution sets. Computational expense is also considered, and opportunities for leveraging a combination of analytical and computational models are discussed.

The layout of this paper is as follows: Section 2 provides relevant background information regarding how FE methods (analytical and computational) and optimization approaches (problem formulation, algorithm development) have been applied to composite panel design problems. The research approach and problem formulations are introduced in Section 3, and results are presented in Section 4. These results are discussed in Section 5 while conclusions and avenues for future work are presented in Section 6.

2. Brief discussion of theoretical foundations

Advancements made in modeling composite panels and optimizing are presented in this section. The goal is not to comprehensively cover all possible research associated with the analysis of composite panels, or different approaches taken toward optimizing them. Rather, prior work advancing the state-of-the-art is highlighted and current limitations are discussed.

2.1. Modeling of composite materials

Early composite analysis used Classical Laminated Plate Theory (CLPT) which was an analytical formulation [9–11]. CLPT enabled researchers to explore simple laminates where only a single ply layer was optimized [10,11]. Other researchers extended the work to predict buckling loads and first ply failure [9]; however, only simple structures (plates or shells) could be considered and the inclusion of multi-angle structures of complex geometry was not permitted. Therefore, researchers naturally expanded into Finite Element analysis, which is capable of predicting the response for much more complicated loading scenarios.

Initial FE models were implemented using in-house codes. For example, initial optimization using these codes centered on plates subjected to transverse pressure and optimized with respect to the mass and deflection [8]. Since then, numerous commercial FE codes have been investigated with different failure theories. Shell elements are often used as the basis of the analysis as they are more computationally efficient than 3D solid elements and are well suited for thin laminate analysis. Plate buckling with first ply failure optimization was performed using the commercial FE code SAMCEF with Hashin failure criteria [13]. Almeida and Awruch consider multiple load case scenarios [16], but the choice of fiber orientation in these analyses was limited to no more than 5 orientation angles. Lee et al. extended the feasible set of fiber orientation angles to 12; however, only a single load case was considered [14].

Computational resource improvements have facilitated the transition from analytical methods of analysis to FE-based computational methods, enabling more complex problems to be explored. Yet, even the computational power offered by a typical desktop computer can result in run times on the order of 15–30 min per simulation. For thousands of iteration calls this can result in a large computational expense. Additionally, optimization algorithms have seen significant advancements in the form of gradient estimation, the creation of new heuristic approaches, and parallelization associated with population-based strategies. Overall, these advancements improve solution quality while simultaneously reducing computational expense, as discussed in the next section.

2.2. Optimization of composite materials

The choice of algorithm used to optimize a composite material often depends on the structure of the problem formulation – discrete or continuous variables, constraints, number of objectives – and the availability of computational resources needed to solve the problem in a timely manner. Techniques used in the literature include direct search techniques [3], gradient-based approaches [3,4], applications of heuristics and greedy behavior [3,12,5,6,17], hybridizations of existing methods [3,18,19], and tailored algorithms that make specific use of composite properties [7,20,21]. Direct search methods eliminate the computational cost associated with calculating the derivative [22], but such approaches are generally applied to problem formulations that contain only a few design variables due to decreased convergence rates [3]. For example, partitioning methods were used in [23] because only a single variable problem was considered. Small design spaces also allow for enumeration strategies [24,25], where the outcomes of the enumeration can be used to guide design space down-selection [26] and to identify which variables have the greatest impact on performance measures [27].

Gradient-based methods offer faster convergence than direct and heuristic methods, but often lack the ability to escape local minimum and require continuous variables for gradient calculation [28] which limit applicability toward composite panel optimization. The limitations of gradient-based approaches for more complex problem formulations, and those with multiple minima, have led to increased application of heuristic and greedy algorithms [3,29]. For example, Irisarri et al. used an Evolutionary Algorithm to maximize the buckling and collapse loads of a composite stiffened panel [13]. The stacking sequences of the skin and stiffeners were determined while maintaining a constant panel mass. Genetic algorithms have also seen increased use when considering objectives such as strength, buckling loads, weight, and stiffness [3] because of their zero-order nature, the ability to tailor algorithm performance, and their ability to find global minimums in multimodal spaces.

The consideration of multiple objectives when formulating the problem requires the use of different classes of optimization algorithms. Early efforts used fiber orientation and a weighted sum approach to maximize prebuckling stiffness, initial postbuckling stiffness and the critical buckling load of uniaxially loaded laminated plates [10]. Walker et al. used a golden section method to determine the Pareto optimal value of fiber angle when maximizing the buckling loads associated with torsional and axial buckling [11]. Genetic algorithms and finite element models have been combined in [8] to simultaneously minimize mass and the deflection of laminated composite structures, and a Pareto-based evolutionary algorithm has been used when minimizing the number of plies while maximizing buckling margins [9].

A challenge of multiobjective problem formulations is that the design space associated with them tends to be quite large. Computational efficiency becomes a significant consideration, and inadequate tuning of heuristic algorithms that lead to poor overall solution quality may further increase computational expense. While analytic models for composite panel design problems may not be as accurate as Finite Element models, the design space is