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Initial sizing optimisation of anisotropic composite panels with T-shaped stiffeners

J. Enrique Herencia, Paul M. Weaver*, Michael I. Friswell

Department of Aerospace Engineering, University of Bristol, Queen's Building, Bristol BS8 1TR, UK

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Abstract

This paper provides an approach to perform initial sizing optimisation of anisotropic composite panels with T-shaped stiffeners. The method divides the optimisation problem into two steps. At the first step, composite optimisation is performed using mathematical programming, where the skin and the stiffeners are modelled using lamination parameters accounting for their anisotropy. Skin and stiffener laminates are assumed to be symmetric, or mid-plane symmetric laminates with 0°, 90°, 45°, or −45° ply angles. The stiffened panel is subjected to a combined loading under strength, buckling and practical design constraints. Buckling constraints are computed using closed form solutions and an energy method (Rayleigh-Ritz). Conservatism is partially removed in the buckling analysis by considering the skin-stiffener flange interaction and decreasing the effective width of the skin. Furthermore, the manufacture of the stiffener is embedded within the design variables. At the second step, the actual skin and stiffener lay-ups are obtained using genetic algorithms, accounting for manufacturability and design practices. This two step approach permits the separation of the structural analysis (strength, buckling, etc.), which is performed at the first step, from the laminate stacking sequence combinatorial problem, which is dealt efficiently with genetic algorithms at the second step.

Keywords: Optimisation; Anisotropic; Lamination parameters; Composite stiffened panels; Closed form solutions; Buckling; Rayleigh-Ritz; Genetic algorithm

1. Introduction

Aerospace manufacturers are increasingly employing laminated composites to replace metallic materials in primary structures in order to reduce aircraft weight. Composite stiffened panels, especially with T-shaped stiffeners, are commonly used to design flight primary structures such as wings or fuselages. In general terms, composite materials present high specific strength and stiffness ratios [1] and offer the advantage over their metallic counterparts of being stiffness tailored. This latter feature is closely associated with their design and manufacture. Laminated composite materials have usually been restricted to symmetric, or mid-plane symmetric laminates with 0°, 90°, 45°, and −45° ply angles, due to practical manufacturing requirements. In addition, the design of composite stiffened panels becomes more complex when considering the manufacture of the stiffener.

Composite optimisation is a non-linear problem. A number of optimisation techniques have been developed over the years to design composite structures [2–29]. In the 1970s, early attempts on optimisation of laminated fibre composites were performed by Schmit and Farshi [2,3]. They optimised symmetric laminated fibre composites with homogeneous and orthotropic properties, considering ply thicknesses as continuous design variables. Stroud and Agranoff [4] followed the same trend and optimised composite hat-stiffened and corrugated panels using a simplified set of buckling equations as constraints. Laminates were assumed to be orthotropic and the design variables were the dimensions of the panel's cross-sections.

However, composites might exhibit a certain degree of flexural anisotropy. Ashton and Waddoups [5] reported the effect of the flexural anisotropy on the stability of composite plates. Chamis [6] concluded that neglecting

*Corresponding author. Tel.: +44 117 9287698; fax: +44 117 9272771.
E-mail address: paul.weaver@bristol.ac.uk (P.M. Weaver).

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flexural anisotropy to assess buckling behaviour could lead to non-conservative results. Nemeth [7] provided the bounds within which flexural anisotropy has a significant effect. Weaver [8,9] recently developed simple closed form (CF) solutions to include the effect of flexural anisotropy on compression and shear loading.

Tsai et al. [10] introduced an alternative representation of the stiffness properties of a laminated composite by the use of lamination parameters. Miki and Sugiyama [11] proposed the use of lamination parameters to deal with the discrete laminate stacking sequence problem. They considered symmetric and orthotropic laminates. Optimum designs for constraints such as in-plane stiffness or buckling, were obtained, from geometric relations between the lamination parameters feasible region and the objective function. Fukunaga and Vanderplaats [12] used lamination parameters and mathematical programming (MP) techniques to carry out stiffness optimisation of cylindrical shells with orthotropic properties. Haftka and Walsh [13] used integer-programming techniques to carry out lay-up optimisation under buckling constraints on symmetric and balanced laminated plates. They used zero-one integers as design variables that were related to stiffness properties via lamination parameters and showed that the problem was linear. Nagendra et al. [14] extended that work and optimised the stacking sequence of symmetric and balanced composite laminates with stability and strain constraints. The drawback of integer-programming techniques is that they require large computational resources especially when structure complexity increases. Fukunaga et al. [15] used MP techniques and lamination parameters to maximise buckling loads under combined loading of symmetrically laminated plates including the bending–twisting couplings (flexural anisotropy). They showed that under shear and shear-normal loading flexural anisotropy could increase or decrease the critical buckling load.

Le Riche and Haftka [16] and Nagendra et al. [17,18] adopted a different approach. They employed genetic algorithms (GAs) to solve the discrete lay-up optimisation problem. GAs are search algorithms based on the mechanics of natural selection and natural genetics [19], which do not require gradient information to perform the search and have the ability to tackle search spaces with many local optima [20]. Furthermore, Nagendra et al. [17] investigated the application of a GA to the design of blade stiffened composite panels. VIPASA [21] was used as the analysis tool and results were compared with PASCO [22], which uses VIPASA as the analysis tool and CONMIN [23] as optimiser. It was concluded that the designs obtained by the GA offered higher performance than the continuous designs. However, it was recognised that great computational cost was associated with the GA. More recently, Liu et al. [24] employed VICONOPT [25] to perform an optimisation of composite stiffened panels under strength, buckling and practical design constraints. A bi-level approach was adopted. VICONOPT was employed at the first level to minimise the panel weight, employing equivalent orthotropic properties for the laminates with continuous thickness, whereas at the second level laminate thicknesses were rounded up and associated with predetermined design lay-ups.

A two-level optimisation strategy employing lamination parameters, MP and GAs, was initially proposed by Yamazaki [26]. The optimisation was split into two stages. Firstly, a gradient-based optimisation was performed using the lamination parameters as design variables. Secondly, the lamination parameters from the first level were targeted using a GA. In this paper, volume, buckling load, deflection and natural frequencies of a composite panel were optimised without accounting for either membrane or flexural anisotropy. Autio [27], following a similar approach to Yamazaki's, investigated actual lay-ups, where certain lay-up design rules were introduced as penalties in the fitness function of the GA.

However, with the exception of Fukunaga and Vanderplaats [12], none of the previous authors considered the feasible region in the lamination parameter space that relates in-plane, coupling and out-of-plane lamination parameters. Liu et al. [28] used lamination parameters and defined the feasible region between two of the four membrane and bending lamination parameters to maximise the buckling load of unstiffened composite panels with ply angles restricted to 0°, 90°, 45°, and -45°. They compared their approach against one using a GA and concluded that the use of lamination parameters in a continuous optimisation produced similar results to those obtained by the GA except in cases where laminates were thin or had low aspect ratios. Diaconu and Sekine [29] performed lay-up optimisation of laminated composite shells for maximisation of the buckling load, using the lamination parameters as design variables and including their feasible region. They fully defined, for the first time, the relations between the membrane, coupling and bending lamination parameters for ply angles restricted to 0°, 90°, 45°, and -45°.

The authors' previous work [30], based upon a two-step optimisation approach, which coupled MP with GAs, showed that composite anisotropy could be used to improve structural performance. Design constraints such as strength, local and global buckling as well as practical design rules were considered. Buckling was addressed by finite elements (FE) and CF solutions. It was shown that CF solutions introduced a high degree of conservatism in the buckling analysis and hence heavily penalised the optimum solutions. However, CF solutions significantly increased the computational efficiency.

The purpose of this paper is to provide an approach to perform initial sizing optimisation of anisotropic composite panels with T-shaped stiffeners. The method divides the optimisation problem into two steps. At the first step, composite optimisation is performed using MP, where the skin and the stiffeners are modelled using lamination parameters accounting for their anisotropy. The skin and stiffener laminates are assumed to be symmetric, or