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Optimal design of triaxial weave fabric composites under tension

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ABSTRACT

Triaxial weave fabrics are increasingly used in ultralight structures, such as the wings of unmanned aerial vehicles (UAVs) and deployable antenna on spacecraft. The tensile strength to stiffness ratio for these applications is important, requiring an optimal weave pattern; in this paper Genetic Algorithms are used to improve these designs. The mechanical response is obtained using the minimum total complementary potential energy principle where the yarns are approximated as curved beams in a micromechanical unit cell. Leading Genetic Algorithms are benchmarked to determine which perform best. The results form a disconnected Pareto front where the left hand part can be used for flexible structures but is difficult to find. An overall improvement in strength to stiffness ratio of 1191% is made with 643 designs found better than a current example. The selection of the Genetic Algorithm is shown to be crucial with only MLSGA-NSGAII regularly finding the entire Pareto front.

1. Introduction

Novel ultralight applications are creating a demand for new materials. These new materials need to have good mechanical properties despite the low mass requirement. Triaxial weave fabrics (TWF), illustrated in Fig. 1, are an example of materials finding growing usage in these structures. They are composites with longitudinal fibres in three directions, 0° and ± 60°, which provide mechanically quasi-isotropic properties, are lightweight due to the high degree of porosity and reduce the impact from air loads. It is also possible to design these structures with a small number of layers, as low as 1. The tensile strength to stiffness ratio is the most important mechanical property in many applications of triaxial weave fabric composites, especially for deployable antenna on spacecraft and ultra-thin wing skins of unmanned aerial vehicles (UAVs) as these properties provide flexible structures that are damage resistant. The crimp, or undulation, of the yarns significantly influences the mechanical properties and requires an optimal weave pattern to maximise the strength to stiffness ratio. However, it is not fully known how close the currently available fibre design schemes are to optimal, since these materials are relatively new.

Genetic Algorithms (GAs) are popular tools for finding optimal composite designs. A review of Composite Structures, Composites Part A, Composites Part B and Composites Science and Technology shows 214 papers utilising Genetic Algorithms to optimise composite structures and materials since 2008. The optimisation problems can be classified into single objective, weighted multi-objective, reducing a multiple objectives problem down to one objective, and multi-objective problems. Multi-objective problems represent the most interesting set as they provide an engineer with a greater understanding of the design space; 39 of the papers found focus on these problems by generating Pareto fronts. Single objective or weighted average problems tend to be easier to solve so a wider range of Genetic Algorithms are capable of solving the problems especially if combined with variable spaces that are small and/or simple.

It is essential to utilise a suitable algorithm for solving an optimisation problem. The 'no free lunch' theorem states that an algorithm that improves its performance on a category of problems inevitably degrades its performance on other types; optimisation algorithms are designed to be specialist to a problem type or have lower performance across all problems. Therefore, a variety of Genetic Algorithms have been developed to solve multi-objective problems categorised by their performance on different types of problems. As an example to demonstrate the importance of selecting the correct algorithm, Mutlu et al. [1] benchmark the performance of a number of popular algorithms on a composite grillage optimisation problem. The problem has limited input variables but even this simple problem demonstrates the need for state-of-the-art algorithms to evolve the entire Pareto front, and that these should be specialist algorithms reflecting the problem type. Reviewing the multi-objective optimisation papers, where a Pareto front is developed, the most popular Genetic Algorithm was NSGA-II but a

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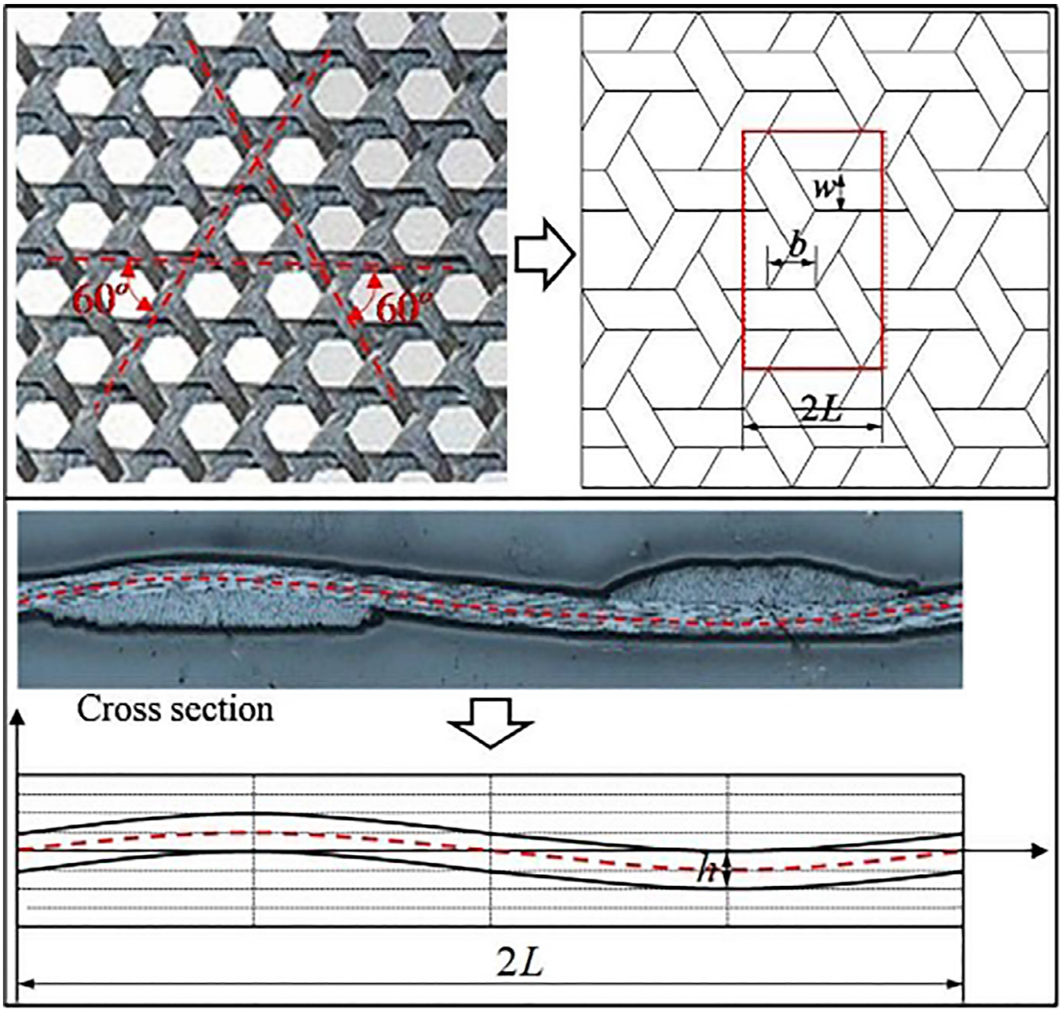

Fig. 1. Unit cell and micrograph of TWF composites [8].

number of older algorithms are still prevalent in this literature. However, in much of the literature the names of the Genetic Algorithms used are not stated, making it difficult to assess the validity of the results.

In addition to the algorithm selection, the hyper-parameters, such as population size, number of generations and mutation and crossover type, affect the performance. From the reviewed literature most of the composite material/structural multi-objective optimisation cases utilise population sizes approximating 600 individuals; this is consistent with the computer science literature where the popular algorithms selected for comparison in the CEC'09 benchmarking use this value or smaller [2]. The reviewed literature generally uses 100 generations or less, totalling 60,000 function calls, including the reviewed woven roving optimisation literature [3–6], with some papers using as few as 350 function evaluations [7]. There is a tendency for the number of function calls to be poorly documented in the composite material/structural optimisation literature and it is suspected that many use smaller numbers to reduce computational time but which may compromise the quality of the final solution. Additionally, the number of repeated independent run cycles is not stated in many papers, with a focus on fewer long runs, indicating that the optimisation results were obtained from one run making it difficult to determine the consistency of the results.

The literature shows promising properties for Triaxial Weave Fabric composites but there is no consensus on which weave patterns provide optimal mechanical characteristics, for example high strength to stiffness ratios. The literature indicates that genetic algorithms are a popular method for optimising composite materials and structures but non-specialist Genetic Algorithms are utilised, many of which are out of date, on single objective or weighted multi-objective problems. It is proposed that current composite structural problems are becoming too complex for these non-specialist algorithms, leading to unresolved Pareto fronts. However, the selection of the correct Genetic Algorithm is difficult as the evolutionary computation literature is not categorised in a manner that reflects composite structures, defining the dominant categories as only constrained or unconstrained formulations for static multi-objective optimisation. Therefore the current study benchmarks state-of-the-art Genetic Algorithms on a multi-objective problem to find optimal designs, Pareto fronts, for TWF composites. The Genetic algorithms considered for the benchmarking are a specialist constrained, MLSGA-NSGAII, a specialist unconstrained, MOEA/D, the most popular, NSGA-II, and one population based local search method, MTS, which demonstrates generally good performance over both formulation types.

2. TWF model for tensile strength and modulus

The tensile modulus and strength of the TWF composites are predicted using the minimum total complementary potential energy principle developed by Bai et al. [8]. Fig. 1 shows the geometry parameters of a unit cell of a TWF composite with the idealized undulation shape of the yarn shown in comparison to a micrograph of the actual undulation. The undulating neutral axis of the triaxial yarns is expressed using a sinusoidal function. The tensile loading is along the 0 degree yarn direction, where the internal forces and bending moments are shown in Fig. 2.