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Two-pheromone Ant Colony Optimization to design dispersed laminates for aeronautical structural applications

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ABSTRACT

The objective of the present study is to find out the effect of using non-conventional fiber orientations (orientations not limited to 0°, ±45° and 90°) to improve the composite material response. The Ant Colony Algorithm is used to optimize the stacking sequence for biaxial tension and compression loading condition under strength constraints. Moreover, a modified algorithm (two-pheromone algorithm) is used to design a fully dispersed laminate. Results show that dispersed laminates can improve the critical buckling load by up to 8% for the biaxial compression loading case. With respect to the biaxial tensile loading condition, the results show that the matrix cracking failure index can be decreased up to 100% and the fiber tensile failure index can be decreased by 40% using the two pheromone formulation.

1. Introduction

The popularity of laminated composite materials in aircraft and spacecraft structures, is not only due to their specific strength and stiffness but also due to their potential for tailoring, by the proper selection of fiber orientations, to meet specific design requirements. The possibility of tailoring stiffness and strength to meet a certain application requirement is directly related to stacking sequence optimization [1,2]. However the use of more traditional manufacturing techniques has limited the use of fiber orientations other than 0°, ±45° and 90°, avoiding the use of more optimized laminates.

Ghiasi et al. [3,4] reviewed the optimization techniques, used for laminated composites, and the characteristics of each algorithm. In that work, it was concluded that gradient direct optimization methods are not suitable for the problem of optimizing the stacking sequence of composite laminates. The reasons are the discrete nature of the problem variables and the huge number of local optima where the gradient methods can converge without reaching the global optimal [1,5]. On the other hand, the enumeration technique can be used for laminates with small numbers of layers and combinations of possible fiber orientations, but for a large number of layers and possible orientations, the enumeration technique fails [6]. The metaheuristic search algorithms are the most suitable to solve the problems in which the objective function can be discontinuous, nondifferentiable, stochastic, or highly nonlinear [7].

Among the metaheuristic methods, Genetic Algorithms (GAs) represent the most commonly used technique in the optimization of laminated composites. The details of the GA optimization method can be found in [8,9]. A huge number of modified GA can be found in the literature; for example GA with local improvement [5,10], Elitist GA [11], GA with the Response Surface method [12], GA with Repair Strategy [13] and the Distributed GA [14]. GA are used often in two-step optimization procedures, that is in a first step, a gradient based algorithm is used to find the set of optimum lamination parameters and in a second step, a GA is used to find the stacking sequence corresponding to the optimum lamination parameters [15,16].

In the last decade, other optimization algorithms were used in problems involving laminated composite materials. Rama Mohan Rao and Arvind [1] used the Scatter Search algorithm, Erdal and Sonmez [17] used the Simulated Annealing algorithm, Karakaya and Soykasap [7] used the Generalized Pattern search algorithm, Todoroki et al. [18,19] used the Fractal Branch and Bound method, Pai et al. [20] used the Tabu-Search, Bloomfield et al. [21] used the Particle Swarm Optimization and Chang et al. [22] used the Permutation Discrete Particle Swarm Optimization.

The Ant Colony Optimization (ACO) algorithm is one of the metaheuristic algorithms that was introduced in the early 1990s by Dorigo et al. [23]. One of the most surprising behavioral patterns exhibited by ants is the ability of certain ant species to find

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what computer scientists call shortest paths. Biologists have shown experimentally that this is possible by exploiting communication based only on pheromones, an odorous chemical substance that ants may deposit and smell [24]. The first use of the ACO in the optimization of composite laminates was in 2008 by Aymerich and Serra [25]. They used an algorithm based on one ant only to optimize the buckling load of laminates. The results included a comparison between the GA and the ACO for different load cases. Following Aymerich and Serra, Bloomfield et al. [6] compared the ACO, the PSO and the GA and they concluded that ACO algorithm is more suitable, in terms of the computational time, for the optimization of a laminate stacking sequence. In another application Hudson et al. [26] showed that the ACO algorithm is the most competitive when designing a sandwich laminate, compared to the SA and the PSO algorithms. In another application (the buckling of stiffened panels) Wang et al. [27] used the ACO method which showed good performance.

This huge effort, spent in laminates stacking sequence optimization, requires manufacturing technologies with higher accuracy. The evolution of the laminated composite materials manufacturing and tooling technologies in aeronautical applications led to the development of fiber placement machines capable of building laminates with a varied number of ply orientations. Only by allowing plies to adopt any orientation within the $-90°$: $90°$ range, can composite laminates exploit their full potential to replace what is the so-called 'black aluminum' (laminates with 0°, ±45° and 90° orientation angles). Moreover, fiber placement machines can fully exploit the anisotropy of composite materials by means of fiber steering, that is laying fibers in curved paths [28]. The industry has not benefit of the huge potential of this technology until recently. By analyzing the results presented in [13,29,30], it becomes clear, that by using dispersed laminates the response of laminated composites can be improved.

Most of the previous studies on stacking sequence optimization either, did not adopt any failure constraints (see for example the work done by Todoroki and Haftka [13]) or used the maximum strain criterion to constraint the problem [5]. Few articles adopted failure criteria that can distinguish between the different failure mechanisms. As an example, Irisarri et al. [29] used the Hashin failure criteria to constraint the problem. Compared to the previous studies, the current paper adopted the LaRC03 failure criteria which distinguish between the different failure mechanisms and, moreover, took into account the nonlinear shear behavior of laminated composites and the in situ strength phenomenon.

The objective of the present study is to find the effect of using non-conventional laminates on the response of laminated composite materials under both biaxial compression and tension loading. A typical conventional lay-up is composed of a number of layers with orientations limited to 0°, ±45° and 90°. Additionally several layers with the same orientation are usually collected together or clustered, (for example $[\pm45_3/90_2/\pm45_4/90_4/0_2]_s$). On the other hand, dispersion means the use of orientations not limited to the conventional ones and the reduction of the number of clustered plies. Two levels of dispersion are used in the current work. The first level is concerning to the design of a laminate at which each layer with θ_1 angle should be followed by another layer with $-\theta_1$ angle ($\theta_1/-\theta_1/\theta_2/-\theta_2/\theta_3/\ldots\ldots/\theta_n/-\theta_n$ where n is the number of design variables). The number of design variables equals one quarter of the number of layers due to balance and symmetry constraints. The second dispersion level concerns the design of a laminate with $\theta_1/\theta_2/\theta_3/\theta_4/\theta_5/\ldots\ldots/\theta_n$ where n is the number of design variables. In this case, the number of design variables is half of the number of layers due to the symmetry constraint. To achieve the balance, each orientation θ_1 should have another orientation $-\theta_1$. To do this, certain forms of dispersion are used and two pheromone matrices are used: one concerns the selection of the dispersion form and the other concerns the design variables. This level was used to check the biaxial tensile case.

2. Ant Colony Optimization

2.1. Basic algorithm

The ACO algorithm is a simulation of the behavior of the real ants when traveling between the nest and the food source [3]. Assuming that one ant travels several times from home to the food source, it must select a certain path on each way. The way by which the ant chooses a certain path instead of another is function of the relative amount of pheromone concentration on the paths. The shortest paths to the food source have higher pheromone concentrations because more ants have successfully adopted them in previous travels.

In our laminate stacking sequence optimization equivalent, each path corresponds to a stacking sequence. In a given optimization iteration (travel) a higher bonus (pheromone concentration), τ_{ij}, is given to the orientations which are part of the best performing stacking sequences. In the next iteration, the probability, P_{ij}^k, of ant k, of choosing the ply orientations with higher bonus is superior.

Consider the simple example shown in Fig. 1. The objective is to design a laminate with $[\theta_1/\theta_2/\theta_3]_s$ with maximum in-plane Young's modulus E_x. Three ants are selected to perform the optimization process. The available orientation angles are 0°, 90°, °45 and $-45°$. The probability of each ant to select a certain orientation angle is the same in the first iteration.

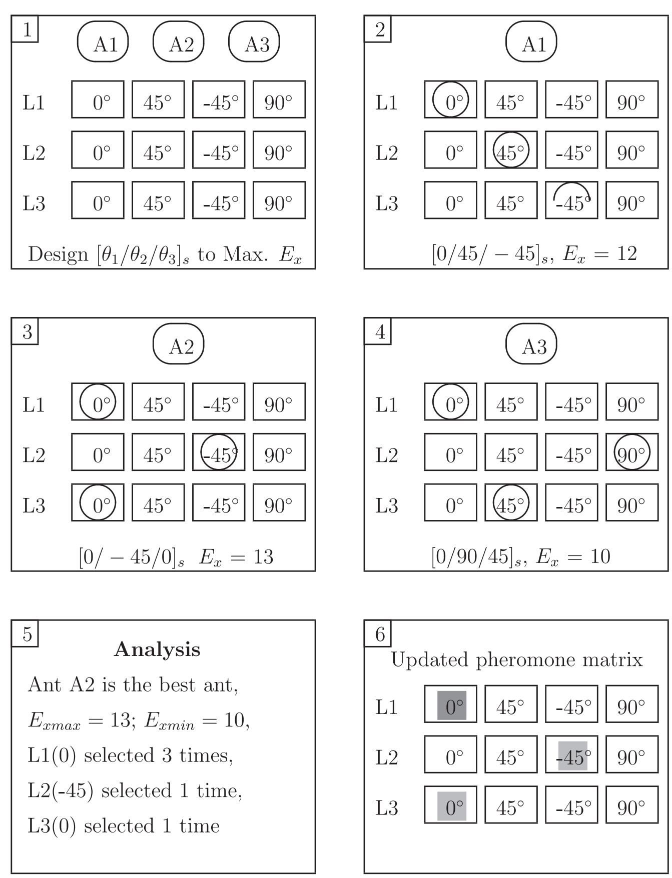

Fig. 1. Simple example of the Ant Colony Optimization algorithm (white color for all orientations in the beginning means equal pheromone concentrations while at the end the gray color concentration follow the pheromone concentration).