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Ant Colony Optimization for dispersed laminated composite panels under biaxial loading

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ABSTRACT

The current study aims to show the benefits of dispersed laminates (laminates in which the orientation angles are not limited to the conventional, 0°, ±45° and 90°, orientations) over conventional ones, in terms of stiffness, buckling resistance and strength, in structural applications. The Ant Colony Optimization algorithm is used with strength constraints to find the best candidate to achieve this goal. A study is conducted to select the most suitable failure criterion among three common ones.

The methodology is used for two loading cases: biaxial compression and biaxial tension. In the case of biaxial compression, the problem is formulated to maximize the critical buckling load whereas with the biaxial tension, the formulation is to minimize the failure index. For both loading cases, the methodology succeeds in improving the response of dispersed laminates with respect to the conventional ones. These results support the movement of the composite industry toward using dispersed laminates.

1. Introduction

The evolution of manufacturing and tooling technologies of laminated composite materials in aeronautical applications has 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 straight-fiber composite laminates exploit their full potential to replace the so-called 'black aluminum' (quasi-isotropic laminates with 0°, ±45° and 90° orientation angles). Although there has been a huge number of studies conducted and still conducted on the optimization of laminate stacking sequence, the industry has not benefited from the huge potential of the current manufacturing technology until recently. Some of this research [1–3] found that tailoring the stacking sequence, without limiting orientations to conventional ones, can improve the laminate response. The ability to tailoring stiffness and strength to meet a certain application requirement is directly related to stacking sequence optimization.

Ghiasi et al. [4,5] 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 [6,7]. On the other hand, the enumeration technique can be used only for laminates with small numbers of layers and combinations of possible fiber orientations [8]. Metaheuristic search algorithms are the most suitable to solve the problems in which the objective function can be discontinuous, nondifferentiable, stochastic, or highly non-linear [9]. Among the metaheuristic methods, Genetic Algorithms (GA) represent the most commonly used technique in the optimization of laminated composites [10–15]. Other metaheuristic techniques were introduced in the literature during the last decade such as the Scatter Search algorithm (SS) [6], Simulated Annealing algorithm (SA) [16], Generalized Pattern algorithm (GP) [9], Fractal Branch and Bound algorithm (FB&B) [17,18], Tabu Search algorithm (TS) [19] and Particle Swarm algorithm (PS) [20].

The Ant Colony (AC) algorithm is one of the metaheuristic algorithms that was introduced in the early 1990s by Dorigo et al. [21]. The first use of the AC in the optimization of composite laminates was in 2008 by Aymerich and Serra [22]. The comparison between the Ant Colony algorithm and other metaheuristic algorithms was introduced by several authors; Aymerich and Serra [22] compared AC with GA, Bloomfield et al. [8] compared the AC, the PS and the GA and Hudson et al. [23] compared AC, SA and PS algorithms. The results of all these comparisons showed a good response of the AC algorithm in terms of both the solution quality and the computational costs.

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The usage of dispersed laminates in stacking sequence optimization studies can be divided into two categories. The first category includes research that modeled the orientation angle as a continuous variable (for example Adali et al. [3]). This approach may lead to a non-optimal or out of feasible region stacking sequence during the manufacturing. The second category includes studies that modeled the orientation angle as a discrete variable (for example Irisarri et al. [2] and Edral and Sonmez [16]). The current paper adopts the discrete modeling of the orientation angles.

From the aeronautical manufacturing point of view, using the dispersed laminates helps to improve the damage resistance but its effect on the damage tolerance is not clear [24]. The damage tolerance is characterized by the buckling capacity of the sublaminates which adds an extra-motivation to the current study.

The current paper describes the effect of using stacking sequences not limited to the conventional orientations. The AC algorithm is selected for this purpose due to its capabilities and the results of the comparisons presented in [8,22,23]. The fiber orientations are modeled as a discrete variable ranging from 0° to 90° with a 5° jump. To achieve symmetry, only one half of the laminate is designed and the other half is defined by mirroring the stacking sequence. To achieve balance, each layer with a $\theta°$ orientation angle is followed by one of $-\theta°$.

The content of this paper is structured as follows. Firstly, the theoretical background of a laminated composite panel under biaxial loading is introduced. Secondly, the Ant Colony algorithm is summarized. Then, a convenient failure criteria is chosen. After that, a flat laminated panel subjected to biaxial loading is analyzed under compression and tension. With respect to the biaxial compression loading case, the problem is formulated so as to maximize the critical buckling load by dispersing the stacking sequence under strength constraints. For the biaxial tension case, the problem is formulated to minimize the failure index (the matrix cracking and the fiber tensile failure indices).

2. In-plane biaxial loading of laminated panels

2.1. Basic relationships

A composite plate under two loading conditions, biaxial tension and compression, is analyzed in the current paper. Although failure mechanisms in the two cases are different (buckling or fiber kinking in the compression case; tensile matrix and fiber failure in the tensile case), the stress strain relations for both cases are similar. By considering only the in-plane deformations, the strains in the global coordinate system corresponding to the biaxial loading are calculated as:

$$\begin{aligned} \varepsilon_x &= a_{11}\lambda N_x + a_{12}\lambda N_y \\ \varepsilon_y &= a_{12}\lambda N_x + a_{22}\lambda N_y \end{aligned} \tag{1}$$

where λN_x and λN_y are the loads in both x and y directions, λ is the load multiplier and a_{ij} are the compliance matrix components. At each lamina i with an orientation angle θ^i, the components of local strain vector $\{\varepsilon\}^i$ are:

$$\begin{aligned} \varepsilon_{11}^i &= \varepsilon_x \cos^2\theta^i + \varepsilon_y \sin^2\theta^i \\ \varepsilon_{22}^i &= \varepsilon_x \sin^2\theta^i + \varepsilon_y \cos^2\theta^i \\ \gamma_{12}^i &= (\varepsilon_y - \varepsilon_x)\sin^2\theta^i \end{aligned} \tag{2}$$

At the lamina level, the local stress vector $\{\sigma\}^i$ is:

$$\{\sigma\}^i = [Q]\{\varepsilon\}^i \tag{3}$$

where $[Q]$ is the in-plane stiffness matrix of the lamina.

Table 1
Hexply AS4/8552 properties [25].

Elastic properties	E_{11} = 128.0 GPa; E_{22} = 7.6 GPa; G_{12} = 4.4 GPa; ν_{12} = 0.35
Strength	X^T = 2035 MPa; Y^T = 26 MPa; X^C = 1531 MPa; Y^C = 200 MPa; S^L = 78.4 MPa
Fracture toughness	G_{Ic} = 0.29 N/mm; G_{IIc} = 0.79 N/mm

With respect to the biaxial compression case, the value of the critical buckling load multiplier λ for a laminated panel can be calculated as [7]:

$$\lambda(p,q) = \pi^2 \frac{D_{11}\left(\frac{p}{a}\right)^4 + D_{22}\left(\frac{q}{b}\right)^4 + 2(D_{12}+D_{66})\left(\frac{p}{a}\right)^2\left(\frac{p}{a}\right)^2}{\left(\frac{p}{a}\right)^2 N_x + \left(\frac{q}{b}\right)^2 N_y} \tag{4}$$

where p and q are the number of half waves in both x and y direction, D_{ij} are the bending stiffness matrix coefficients and a and b are the specimen length and width, respectively.

The material used for the current investigation is the AS4/8552 carbon/epoxy. The unidirectional elastic, strength and fracture properties are listed in Table 1 [25].

2.2. Failure criteria

Amongst more than 40 failure criteria developed for laminated composite materials, the maximum strain criterion is the most commonly used in the optimization of the stacking sequence, and the Tsai-Wu one is the most commonly used in the industry [26]. These two failure criteria are very simple in terms of formulation and implementation which means a low computational effort. On the other hand, these criteria do not consider some of the influencing variables in the failure process of laminated composite i.e. they do not take into account the effect of shear non-linearity, lamina position and thickness (the in situ strength) on the predicted failure index.

During the last few decades, many physically-based failure criteria have been developed to be more suitable for laminated composites. Although this type of failure criteria is proven to achieve trustworthy results, the number of studies that adopt them is still small (for example Lopez et al. [27] and Kober and Kühhorn [28]) due to the required computational effort. The LaRC03 failure criteria [29] fall into this category of physically-based failure criteria and have been selected to conduct the current study. Moreover, the criteria adjust the strength of the ply depending on its relative position in the laminate (the in situ strength phenomena) and take into account the non-linear in-plane shear deformation behavior.

2.3. Optimization problem formulation

For the plate under biaxial compression, the optimization problem is formulated to maximize the load multiplier λ under failure constraints (the panel is considered to fail if it buckles or if any of the failure indices exceeds 1). With respect to the biaxial tensile loading conditions, two formulations are considered. The first formulation considers the matrix cracking (FI_{MT}) as the most important failure index. The second one considers equal importance of the matrix cracking and the fiber tensile (FI_{FT}) failure indices (multi-objective optimization). The differences between the three different formulations are shown in Table 2.

Symmetry and balance constraints are taken into account when building the algorithm. The symmetry is achieved by designing only one half of the laminate and mirroring the second half. The balance is achieved by assuming that each layer oriented at an angle of θ should be followed by another layer at an angle of $-\theta$,