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Stacking sequence optimization for maximizing the first failure initiation load followed by progressive failure analysis until the ultimate load

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ABSTRACT

For laminated plates deformed statically with transverse normal tractions applied on a major surface, we use honeybees inspired Nest-Site Selection (NeSS) optimization algorithm, a third order shear and normal deformable plate theory (TSNDT), and the finite element method to find an optimum stacking sequence that maximizes the first failure load according to the Tsai-Wu criterion. An optimum lay-up of fibers in different layers depends upon the starting estimate and is not unique. In the TSNDT, we express each displacement component at a point as a complete polynomial of degree three in the thickness coordinate. Subsequent to finding an optimum stacking sequence, we perform progressive failure analysis to determine the ultimate load by degrading elasticities of the material at an integration point where the failure criterion has just been satisfied. Without incrementing the load, we repeat the analysis to find if the failure at one integration point has led to failure at other integration points. When the failure ceases to propagate, we increase the load and repeat the analysis. We take the degradation of material properties to be permanent. At the ultimate load deflections of one or more points become extremely large with a minute increment in the applied load. We also find the ultimate load for different load distributions on a major surface, boundary conditions and plate geometries. It is found that for a clamped plate, the ultimate load can be 40% more than the first ply failure load. However, for a simply supported plate, the ultimate load essentially equals the first failure load. The stacking sequence for the optimal first failure load need not have the maximum ultimate load.

1. Introduction

Fiber-reinforced composite laminates are being increasingly used due to their high specific strength and stiffness as compared to those of metals. Furthermore, the fiber volume fraction and the fiber direction can be tailored to meet specified strength requirements at critical points and in desired directions. The effective utilization of composite structures for a given application requires optimizing their design by varying, for example, the total number of layers, the fiber angle in each layer, the layer thickness, the fiber volume fraction in each ply, and the stacking sequence. Typical objective functions include the maximum specific strength and/or stiffness, the maximum fundamental frequency, the maximum deflection, and the probability of failure.

Bio-inspired optimization algorithms such as the Genetic Algorithm (GA) [1], the Particle Swarm Optimization (PSO) [2], the Ant Colony Optimization (ACO) [3], and the Artificial Bee Colony (ABC) [4] have been successfully used to optimize designs of composite laminates. A GA simulates the natural evolution in which parents reproduce offsprings by passing down their genes. The strength of an offspring depends on characteristics inherited from their parents, and only a strong offspring is assumed to survive. The PSO algorithm was motivated by social behaviors of bird flocks and fish schools, while the ACO and the ABC algorithms were developed by observing the foraging behaviors of ant colonies and honeybee swarms, respectively.

Nagendra et al. [5], Gyan et al. [6], Omkar et al. [7], Narayana et al. [8], and Kaveh et al. [9], amongst others, have used the bio-inspired algorithms to design minimum weight laminated structures for given applied loads. Nagendra et al. [5] modified the GA by introducing a new mutation technique to design the stacking sequence of the minimum weight panels. They claimed that the improved GA reduces the computation cost, increases reliability and gives lighter designs than those obtained from the original GA. Gyan et al. [6] used the GA to optimize the stacking sequence by varying angles at intervals of 5° between adjacent plies so that none of the material particles satisfied the Tsai-Wu failure

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criterion. Their results showed that for the same loads and the laminate weight the unconventional stacking sequence has better damage tolerance than the traditional layup since it increases the crack fiber bridging at the interfaces that reduces interlaminar shear stresses. A discrete version of the Vector Evaluated Particle Swarm Optimization Algorithm (VEPSOA) has been applied to design composite laminates by Omkar et al. [7] and Narayana et al. [8]. Omkar et al. computed the number of layers, the layer thicknesses, and the stacking sequence to minimize the weight and the manufacturing and material costs. Narayana et al. compared performances of the VEPSOA and the GA for designing the minimum weight laminates under several loadings and different failure criteria including the maximum stress, the Tsai-Wu and the mechanism based failure criteria. The VEPSOA and the GA gave the same minimum weight configurations. The hybrid algorithm comprised of the Charged System Search (CSS) and the PSO algorithms was proposed by Kaveh et al. [9] to enhance the process for optimizing the number of plies and their orientations for the minimum weight of composite plates under in-plane loading without failure initiating at any material point.

Walker and Smith [10] proposed combining the finite element method (FEM) and the GA to minimize the sum of the total non-dimensional mass and the non-dimensional deflection of fiber-reinforced structures. Aymerich and Serra [11] employed the ACO algorithm to find the laminate stacking sequence that minimizes the strain energy of deformation for given either in-plane or transverse loadings while keeping the layer thicknesses and the total number of layers fixed. By using the ABC algorithm and the FEM, Apalak et al. [12] found optimal stacking sequences of a symmetric laminate that maximized the fundamental frequency for various boundary conditions, plate thicknesses, and the length to width ratio. They stated that the ABC algorithm has fewer control parameters and simpler structure than the GA, and the two algorithms give the same optimum solutions. Batra and Jin [13] considered continuous through-the-thickness power-law variation of the fiber orientation angle in a laminate and found the power-law index that optimizes the laminate fundamental frequency.

Many researchers have optimized composite structures with multiple objectives. For example, Callahan and Weeks [14] used the GA to determine ply orientations for the maximum strength and/or stiffness and the minimum weight, and validated their results by comparing them with either exact or known solutions. They reported that the GA required long execution times to identify the optimal solution for a large number of plies. Abachizadeh and Tahani [15] used the ACO algorithm to design hybrid laminates with the maximum fundamental frequency and the minimum strain energy by adjusting the stacking sequence of hybrid graphite/epoxy-glass/epoxy laminated plates, the number of plies, and ply orientations. They reported that the ACO algorithm could find the global optimal solution in all cases including those for which the GA could not. Omkar et al. [16] used a discrete version of the Vector Evaluated Artificial Bee Colony (VEABC) and the GA algorithms to optimize the number of plies, ply orientations, and thickness of each layer under constraints of minimum weight, least total cost and no failure occurring according to either the mechanism based or the maximum stress or the Tsai-Wu criterion. The two algorithms gave the same solutions that agreed with that obtained using the PSO algorithm by other investigators. They stated that the VEABC algorithm is robust and flexible to deal with additional objectives and constraints.

Hare et al. [17] compared non-gradient optimization algorithms, such as the GA, the PSO, and the ACO, in several structural optimization applications. They remarked that the GA is adaptable for various types of optimization problems, however, it did not give the best value of the objective function as compared to that derived by using other algorithms.

It should be evident from the preceding overview that one algorithm does not give the best solution for every structural mechanics problem. The ACO algorithm was originally proposed for combinatorial optimization problems that involve discrete values of variables. Although the GA, the PSO, and the ABC algorithms were developed for problems in which the design variables continuously vary, they have been modified in a number of studies to allow for discrete values of design variables. The performances of the GA, the PSO algorithm, and the ABC algorithm have been compared for several benchmark functions that include unimodal and multimodal distributions [18,19]. None of these three algorithms outperformed others in terms of the CPU time for every benchmark function used. The analyses of many other problems have indicated that the ABC algorithm is more suitable than the GA for optimizing functions of several variables that have many local minima. Singh [20] has shown that the ABC algorithm also performs better than the ACO algorithm in combinatorial optimization problems.

In structural problems, understanding the failure of composite laminates has been a subject of intense research. Reddy and Pandey [21] analyzed the first-ply failure of composite laminates using the first-order shear deformable theory (FSDT) and the maximum stress, the maximum strain, the Hill, the Tsai-Wu, and the Hoffman failure criteria. The first-ply failure of composite laminates subjected to different loadings and boundary conditions has also been studied, amongst others, by Bruno et al. [22], Kam et al. [23], Ray and Satsangi [24], Prusty et al. [25], and Ramtekkar et al. [26]. The first-ply failure load, however, does not generally equal the ultimate load for a structure.

A progressive failure analysis (PFA) in which a failed element is either deleted or has material elasticities severely degraded and the analysis continued with the applied load incrementally increased is needed to find the ultimate load for the structure. A total discount approach is the simplest method in which the stiffness properties of a failed ply are set equal to zero. For example, Pal and Ray [27], Prusty [28], and Gadade et al. [29] used the total discount approach to analyze the progressive failure of composite plates. Petit and Waddoups [30], Reddy and Reddy [31], Liu and Tsai [32], Padhi et al. [33], and Kress et al. [34], amongst others, reduced the stiffness of a failed ply based on either the matrix or the fiber failure.

The residual property method based on continuum damage models is another way to degrade material properties. Examples of the continuum damage mechanics in the analysis of composites include works of Lo et al. [35], Barbero and Lonetti [36], Feih and Shercliff [37], Turon et al. [38], Hassan and Batra [39] and Batra et al. [40].

We note that most studies on the stacking sequence optimization and the PFA of laminated plates have focused on in-plane loadings. Here we determine the fiber orientation angle in each layer of a rectangular laminate deformed statically by transverse loads applied on a major surface that maximizes the first ply failure load according to the Tsai-Wu failure criterion and employs the Nest-Site Selection (NeSS [41]) optimization algorithm based on the behavior of honeybees. The laminate deformations are analyzed with a third order shear and normal deformable plate theory (TSNDT). A one-step stress recovery scheme (SRS) is employed to find the transverse shear and the transverse normal stresses from the in-plane stresses determined from the plate theory solution. In the TSNDT, each displacement component at a point is expressed as a complete polynomial of degree three in the thickness coordinate. The SRS involves integration of the 3-dimensioanl (3-D) equilibrium equations along the thickness direction starting from a major surface of the plate. Shah and Batra [42–44] studied deformations of laminated plates and doubly curved shells using the TSNDT and the SRS, and their results for stress distributions including stress singularities near the laminate