



Artificial Bee Colony (ABC) for multi-objective design optimization of composite structures

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ARTICLE INFO

Article history:

Received 18 August 2008
Received in revised form 4 November 2009
Accepted 6 December 2009
Available online 16 December 2009

Keywords:

Swarm intelligence
Artificial Bee Colony (ABC)
Vector Evaluated Artificial Bee Colony (VEABC)
Composite
Structural optimization
Multi-objective optimization

ABSTRACT

In this paper, we present a generic method/model for multi-objective design optimization of laminated composite components, based on Vector Evaluated Artificial Bee Colony (VEABC) algorithm. VEABC is a parallel vector evaluated type, swarm intelligence multi-objective variant of the Artificial Bee Colony algorithm (ABC). In the current work a modified version of VEABC algorithm for discrete variables has been developed and implemented successfully for the multi-objective design optimization of composites. The problem is formulated with multiple objectives of minimizing weight and the total cost of the composite component to achieve a specified strength. The primary optimization variables are the number of layers, its stacking sequence (the orientation of the layers) and thickness of each layer. The classical lamination theory is utilized to determine the stresses in the component and the design is evaluated based on three failure criteria: failure mechanism based failure criteria, maximum stress failure criteria and the tsai-wu failure criteria. The optimization method is validated for a number of different loading configurations—uniaxial, biaxial and bending loads. The design optimization has been carried for both variable stacking sequences, as well fixed standard stacking schemes and a comparative study of the different design configurations evolved has been presented. Finally the performance is evaluated in comparison with other nature inspired techniques which includes Particle Swarm Optimization (PSO), Artificial Immune System (AIS) and Genetic Algorithm (GA). The performance of ABC is at par with that of PSO, AIS and GA for all the loading configurations.

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1. Introduction

Now-a-days composites are becoming increasingly popular, due to their superior mechanical characteristics, like very high stiffness to weight ratios and amenability to tailoring of these properties. Remarkable variations in the characteristics of composite materials can be achieved by slightly altering their properties. Thus, composite materials offer the possibility to create an unlimited set of different material behaviors that can be tailored to specific structural needs. The use of laminates increases the freedom in design and gives more control to fine-tune the material to meet local design requirements. However, the analysis and design of composite materials is relatively more complex. Composite design optimization typically consists of identifying the optimal configuration that would achieve the required strength with minimum overheads. The possibility to achieve an efficient design that fulfills the global criteria and the difficulty to select the values out of a large set of constrained design variables makes mathematical optimization a natural tool for the design of laminated composite

structures [1]. Depending on the nature of application for which the component is being designed, there would be a number of different overheads like weight, cost, etc which have to be taken into consideration for effective design optimization of composites. Thus, making this problem multi-objective in nature. There has been considerable amount of work carried out on composites' design optimization [1–7]. Laminate stacking sequence design optimization has been formulated as a continuous optimization problem and solved using various gradient based methods by Gürdal and Haftka [2]. Bruyneel [3] has presented a general and effective procedure based on a mathematical programming approach for the optimal design of composite structures subjected to weight, stiffness and strength criteria. Shin et al. [4] have investigated the minimum-weight design of simply supported, symmetrically laminated, thin, rectangular, especially orthotropic laminated plates for buckling and post-buckling strengths. Adali et al. [5], Kumar and Taichert [6] and Pelletier et al. [7] have discussed the multi-objective design of symmetrically laminated plates for different criteria like strength, stiffness and minimal mass. Venkataraman and Haftka [8] have presented a review of various approaches to the optimization of composite panels.

Composite laminate design problems typically involve multi-modal search spaces [8] with the design variables capable of taking

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Nomenclature

a, b, h length, width, thickness of the plate
 E_{LL}, E_{TT}, E_{tt} longitudinal, transverse, normal elastic moduli
 G_{LT}, G_{Lt}, G_{Tt} shear moduli in longitudinal, lateral and traverse directions
 N, α, β, γ number of artificial bees, randomness amplitude of bee, convergence rate, learning rate
 $N_x, N_y, N_{xy}, M_x, M_y, M_{xy}$ stress resultants, moment resultants in X – Y plane
 S shear strength in the X – Y plane
 t_k, θ, N ply thickness, stacking sequence, number of plies
 $\nu_{LT}, \nu_{Lt}, \nu_{Tt}$ lamina Poisson's ratio's in longitudinal, lateral and traverse directions

Greek symbol

$\sigma_{LL}, \sigma_{TT}, \sigma_{LT}$ longitudinal, transverse, shear stress along material axes

a wide range of values, making this a combinatorially explosive problem. For such problems, traditional gradient based algorithms are plagued with the problem of converging to locally optimal regions of the design space. Multi-objective design of composites warrants the use of modern non-parametric optimization methods.

In pursuit of finding solution to these problems many researchers have been drawing inspiration from the nature. A host of such nature inspired techniques have been developed namely Genetic Algorithm (GA) [9], Artificial Neural Networks (ANN) [10], Particle Swarm Optimization (PSO) [11,12] and Artificial Immune System (AIS) [13]. These algorithms with their stochastic means are well equipped to handle such problems. Of these, GA has been a very popular tool for the combinatorial design optimization of composite structures [9]. It has been extensively employed for the optimal structural design and there are numerous successful implementations available in the literature for the same [9,14–19].

In the current work, we present a generic multi-objective approach for the composite design optimization based on another such, relatively new swarm intelligence technique—Artificial Bee Colony (ABC) [20]. Swarm intelligence algorithms are a new range of computational algorithms that have emerged from the behaviour of social insects. Social insects are usually characterized by their self-organization (in numerous situations the coordination arises from interactions among individuals) and the absence of central control. Still, complex group behaviour emerges from the interactions of individuals who exhibit simple behaviours by themselves. In social insects, every individual is autonomous. They can only obtain local information, and interact with their geographical neighbours. All these features characterize swarm intelligence. Examples of systems like this can be found in nature, including bee colonies, ant colonies, bird flocking, animal herding, fish schooling etc. Inspired by the bee behaviour, Artificial Bee Colony [20] is one of the generally applicable techniques used for optimizing numerical functions and real-world problems. Compared with GA and other similar evolutionary techniques, ABC has some attractive characteristics and in many cases proved to be more effective [20]. Both GA and ABC have been used extensively for a variety of optimization problems and in most of these cases ABC has proven to have superior computational efficiency [20,21]. Further, ABC does not use any gradient-based information. It incorporates a flexible and well-balanced mechanism to adapt to the global and local exploration and exploitation abilities within a short computation time. Hence, this method is efficient in handling large and complex search spaces. ABC with its ability to handle

combinatorial explosive problems appears to be very promising for the multi-objective optimization problem addressed in this paper.

The multiple objectives considered here are—minimizing the weight of the composite component and also minimizing the total cost (manufacturing and material costs). The primary design variables are—number of layers, lamina thickness and the stacking sequence. These variables are altered so as to attain an optimum composite design that achieves both the above mentioned objectives while satisfying the specified strength requirements. In the current work, the stacking sequence is not restricted to the popularly used schemes like {0/45/90}, {0} and {0/90}. Instead, the ply orientation angles are also considered as variables of the optimization process, thereby allowing for evolving new non-standard stacking schemes, appropriate for the specified application. This ensures a truly optimal design for the given application as all the possible stacking sequences are explored. The classical lamination theory is utilized to determine the stresses at each layer for thin laminates subjected to force and/or moment resultants and the design is evaluated based on the specified failure criteria. The use of appropriate failure criteria is crucial for the optimal design of composite laminates. Since different failure mechanisms are relevant for different loading combinations, in the current work we evaluate the composite design for three different failure criteria; Tsai-Wu [22], Maximum Stress [1] and the Failure Mechanism based criteria [23]. This makes the optimization method truly generic and ensures a completely optimum solution/configuration for the given application.

The generic composite design optimization framework being presented in the current work employs Vector Evaluated Artificial Bee Colony (VEABC), a variant of the classical ABC for multi-objective optimization. This method allows for separate evaluation of the multiple objectives, which proves to be very appropriate for the current problem. This is a swarm intelligence method which employs separate swarms for each of the objectives and information migration between these swarms ensures an optimal solution with respect to all the objectives.

This paper is structured as follows: basics of multi-objective problems are presented in Section 2. Section 3 introduces ABC and VEABC. Details of the problem and its formulation are explained in Section 4. The outline of the optimization process employed is given in Section 5. The numerical results and discussions are presented in Section 6. Finally, the comparison of nature inspired techniques and conclusions are given in Sections 7 and 8 respectively.

2. Multi-objective optimization

Let X be a n -dimensional search space, and $f_i(x)$, $i=1..k$, be k objective functions defined over X . Furthermore, let $g_i(x) \leq 0$, $i=1..m$, be m inequality constraints. Then, the multi-objective problem can be defined as finding a vector, $x=(x_1, x_2, \dots, x_n)^T \in X$ that satisfies the constraints, and optimizes the vector function,

$$f(x) = \{f_1(x), f_2(x), \dots, f_k(x)\}^T. \quad (1)$$

In the case of multi-objective problems the concept of *Pareto optimality* [24,25] is introduced. A solution x of the multi-objective problem is said to be *Pareto optimal* if and only if there does not exist another solution y , such that $f(y)$ dominates $f(x)$. The objective functions $f_i(x)$, may be conflicting with each other, thus, most of the time it is impossible to obtain for all objectives the global minimum at the same point. Instead there exists a set of optimal trade-offs which forms the solution set—the *Pareto set* and it is denoted by P^* . The set $PF^* = \{f(x) | x \in P^*\}$ is called the *Pareto front*.

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