BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Tomul LIX (LXIII), Fasc. 6, 2013
Secția
CONSTRUCȚII. ARHITECTURĂ

MODERN APPROACHES ON THE OPTIMIZATION OF COMPOSITE STRUCTURES

BY

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Received: November 3, 2013
Accepted for publication: November 27, 2013

Abstract. A laminated fibre reinforced composite structure is usually tailored, according to the design objectives, by choosing the individual constituents and of their volume fractions, the fiber orientation, the laminae thicknesses and orientation of the plies, their number and stacking sequences, as well as the fabrication procedure. To achieve the best results, optimization techniques have been developed. In recent years, some optimization methods, that are conceptually different from the traditional mathematical programming techniques, have been developed. These methods are labeled as modern or nontraditional methods of optimization. This paper provides a review of modern optimization methods, used for the design of composite structures: Genetic Algorithm (GA), Simulated Annealing Method (SAM), Particle Swarm Optimization Algorithm (PSOA) and Ant Colony Optimization (ACO). The existing published studies emphasize the suitability of these methods, which allows that many design parameters and constraints to be used in the optimization process of composite structures.

Key words: optimization design; composite structures; stochastic method.

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1. Introduction

Optimization is a method to determine the best possible solutions, using a set of mathematical eqs. that represent a physical system. Optimization techniques play an important role in an efficient structural design, the very purpose of which is to find the best ways so that a designer or a decision maker can derive a maximum benefit from the available resources.

The shortcomings of the indirect design can be overcome by adopting a direct or optimal design procedure. The main characteristic of optimal design is that it consists of only logical decisions.

The problem of optimization may became a multi-objective optimization problem, having to minimize, for example, both the weight and the total cost for a composite, subjected to a required strength, so that it satisfies the specified failure criteria. The decision variables considered are: the number of layers, stacking sequence and the lamina thickness; these variables have very wide ranges and are associated with a number of different constraints.

Nowadays methods for global laminate optimization are often limited to analytical geometries (Messac *et al.*, 2002), leading to optimized designs which need interpretation by an expert (Hansel *et al.*, 2002), or are limited to few design objectives such as minimum compliance (Kocvara, 2000).

Designing laminated composites has become a challenging problem for the designer because of a wide range of parameters that one can play with, and because the complex behavior and multiple failure modes of these structures require sophisticated analysis techniques. The possibility of achieving an efficient design that is safe against multiple failure mechanisms, coupled with the difficulty in selecting the values of a large set of design variables, makes structural optimization an efficient tool for the design of laminated composite structures (Haftka *et al.*, 1992).

The potential capabilities of laminated composites have led many researchers to implement different algorithms to produce the most suitable structure for a typical application. Optimizing the design of civil engineering structures was done to meet specific design requirements or constraints for the structure over its design life.

This work reviews the most popular optimization methods used in the design of composite structures for civil engineering applications.

2. Methods Used in Optimization Design of Composite Structures

The search and optimization techniques are broadly classified into three main categories (Gürdal *et al.*, 1999) (Fig. 1).

Stochastic or probabilistic programming methods deals with situations where some or all of the parameters of the optimization problem are described by stochastic (or random, or probabilistic) variables, rather than by deterministic quantities. The basic idea used in stochastic programming is to convert the stochastic problem into an equivalent deterministic problem. The resulting deterministic problem is then solved by using familiar techniques such as linear, geometric, dynamic, and nonlinear programming.

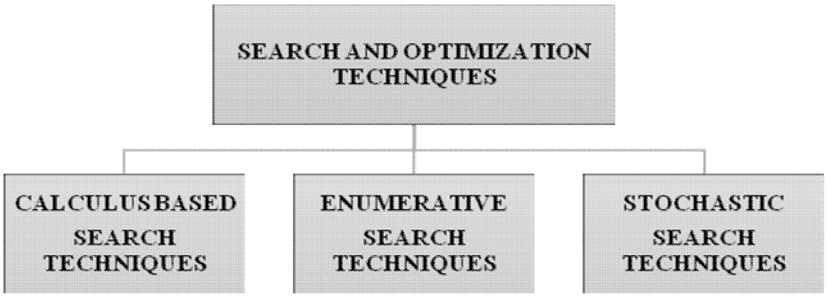

Fig. 1 – Classification of available search techniques.

Nature inspired techniques such as Genetic Algorithm (GA) (Goldberg, 2005), Artificial Immune System (AIS) (Omkar *et al.*, 2008), Particle Swarm Optimization (PSO) (Omkar *et al.*, 2008), etc., provide a more robust and efficient approach in solving real-world complex problems of optimal structural design. The Genetic Algorithm (GA) and Simulated Annealing Method (SAM) are two of the most popular stochastic optimization techniques.

This work reviews the most popular optimization methods used in the design of composite structures for civil engineering applications.

2.1. Genetic Algorithm (GA)

Genetic algorithm (GA) is a part of evolutionary computing, which is a rapidly growing area of artificial intelligence. The GAs are based on the principles of natural genetics and natural selection. Because GA are based on the survival-of-the-fittest principle of nature, they try to maximize a function called the *fitness function*. The population is updated after each learning cycle through three evolutionary processes: selection, crossover and mutation. These create the new generation of solution variables (Fig. 2).

In the last few decades, GAs have been used in the structural design optimization, due to their capability to deal with complicated and large variable problems. The fundamental theorem of the GA was developed by Holland (Burns, 2002; Tabakov & Walker, 2010). GAs are used in optimizing the fiber-reinforced polymer composite plate where objective set was to minimize the weight and the cost of a fiber-reinforced polymer plate as shown in Fig. 3, where objective set was to minimize the weight and the cost of a fiber-reinforced polymer plate.

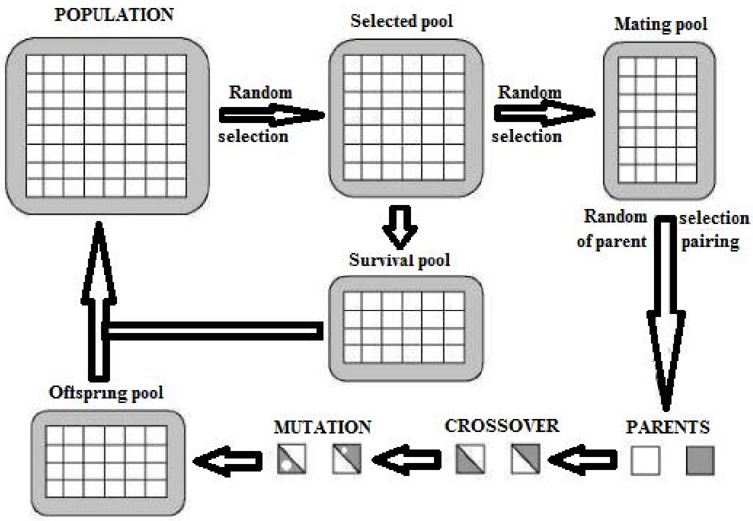

Fig. 2 – A GA iteration cycle (Nanda, 2009).

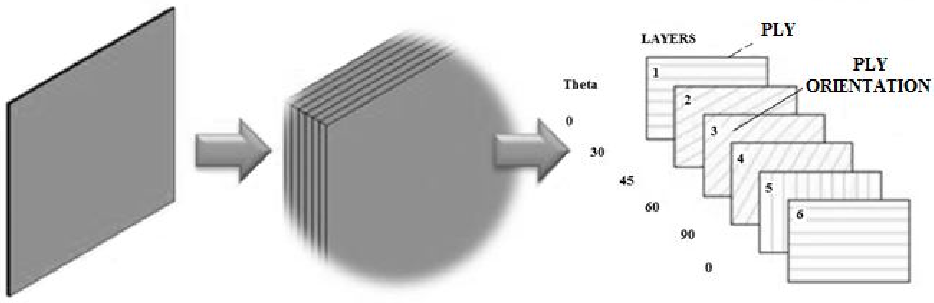

Fig. 3 – Composite laminate orientations (Parle, 2013).

For the first time, Callahan and Weeks, (1992), proved that GAs can be a viable alternative to traditional search procedures in the design of composite laminates. Kogiso *et al.*, (1994), used GAs with local improvement to optimize a laminated composite plate for buckling load maximization. Many others authors utilized this method or the modified type to optimize strength-to-weight ratio or other parameters (Soremekun *et al.*, 2001; Riche & Haftka, 1994; Muelas *et al.*, 2008). Other authors used this method and various failure mechanism based on different failure criterion (Narayana Naik *et al.*, 2008). Niranjan *et al.*, (2003), tried to optimize stacking sequence of a laminate for buckling response, matrix cracking and strength. The searches that were conducted were based on a heuristic search technique, known as Tabu Search (TS), and the results were confronted with those of genetic algorithms.

The optimization of composite structures using parallel genetic algorithms gives a relatively good convergence with reasonable process time. In addition, the quality of the result depends on the size of the problem.

Rahul *et al.*, (2006), developed a multiple objective optimization technique using a GA in combination with a finite element method, in order to simultaneously minimize the cost and weight of a composite plate. Walker & Smith, (2003), used a similar coupling to minimize the weight and deflection of laminated plates for different loading and boundary conditions.

One of the GA main advantages is the capability to treat multimodal functions, finding its multiple optima and giving the possibility to choose one solution (design) or another. Also, GA do not use any gradient information during the searching process, in contrast to numerical optimization procedures, making them a good compromise between expensive brute force search strategies and numerical approaches.

2.2. Simulated Annealing Method (SAM)

This method is the most popular method after GA for stacking sequence optimization of laminated composite materials.

SAM is based on the simulation of thermal annealing of critically heated solids and is an iterative search method inspired by the annealing of metals. Starting with an initial solution and armed with adequate perturbation and evaluation functions, the algorithm performs a stochastic partial search of the design space. Uphill moves are occasionally accepted with a probability controlled by a parameter called *temperature* (T). The probability of acceptance of uphill moves decreases as T decreases. At high temperature, the search is almost random, while at low temperature the search becomes almost greedy. At zero temperature, the search becomes totally, *i.e.*, only good moves are accepted (Kirkpatrick et al, 1993).

Both GA and SAM are stochastic methods that can find the global minimum with a high probability and can be used to find the solutions of discrete optimization problems.

Kirkpatrick *et al.*, (1993), are one of the first that proposed SAM as a powerful stochastic search technique. SAM is superior to other optimization algorithms because it is generally more reliable in finding the global optimum, *i.e.* the probability of locating the global optimum is high even with large numbers of design variables. Another advantage of simulated annealing is that it does not require derivatives of objective function or constraint functions, being, like GAs, a zero order algorithm. The main drawback, on the other hand, is the requirement of quite a number of iterations for convergence, but with the today's ever increasing computational power, this is becoming less and less a problem.

In structural design, SAM was used to find the optimum design of fiber composite structures as an efficient method to solve problems with multiple-global optima (Hasançebi *et al.*, 2010). Erdal & Sonmez, (2005), maximized buckling load capacity using simulated annealing method (SAM). Also Akbulut & Sonmez, (2008), carried out direct simulated annealing (DSA) to minimize thickness of laminated composite plates, subject to in-plane loading. Rao *et al.*, (2002), optimized composite plate design in order to maximize the natural frequency as a dynamic consideration by using the SAM. They found that this method is a less expensive method to deal with complicated design optimization, especially when the design considers the layup optimization as well as the ply orientations. Ertas & Sonmez, (2010), used the SAM to design fiber composite structure for maximum fatigue life. They found that increasing the number of fiber angles improved the fatigue life of the structure.

Rao & Arvind, (2007), found that SAM is strengthened by embedding TS in order to prevent recycling of recently visited solutions and the resulting algorithm is referred to as Tabu embedded Simulated Annealing (TSA) algorithm. Computational performance of the proposed TSA algorithm is enhanced through cache-fetch implementation.

2.3. Particle Swarm Optimization Algorithm (PSOA)

The PSOA is based on the behavior of a colony of living things, such as a swarm of insects like ants, termites, bees, and wasps; a flock of birds, or a school of fish. A swarm is a group of multi-agent system such as bees, in which simple agents coordinate their activities to solve the complex problem of the allocation of labor to multiple forage sites in dynamic environments.

In PSOA a swarm consists of a set of volume-less particles (a point) moving in a *D*-dimensional search space, each representing a potential solution. Each particle flies in the search space with position and velocity which are dynamically adjusted according to its own as well as its companions flying experiences. The concept of movement of particles of particle swarm optimization algorithm is described in Fig. 4.

Optimization methods based on swarm intelligence are called *behaviorally-inspired algorithms* as opposed to the genetic algorithms, which are called *evolution-based procedures*. The particle swarm optimization algorithm was originally proposed by Kennedy & Eberhart, (1995).

PSOA is an algorithm, which is based on swarm intelligence (Lee *et al.*, 2012). It was developed from a research on the bird and fish flock movement behavior. PSOA consists of group of particles and the position of each particle is affected by the surrounding the optimal position during its movement.

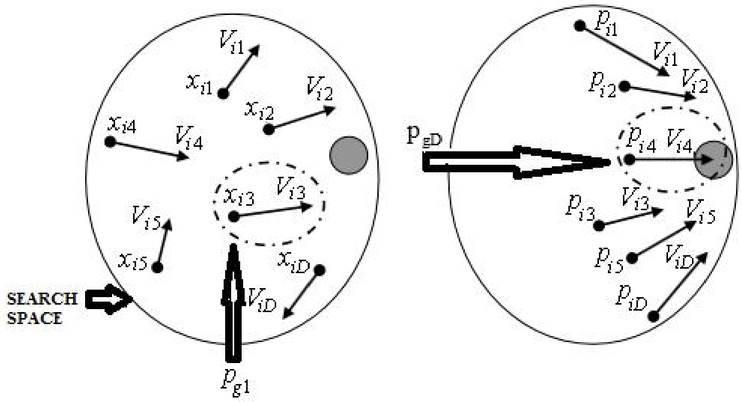

Fig. 4 – Representation of PSOA: *a* – initialization, *b* – particles movement towards solution (Nanda, 2009).

Optimum design of a sandwich panel structure was conducted by Kovács *et al*., (2004), Narayana Naik *et al*., (2011), Omkar *et al*., (2008) used Vector Evaluated Particle Swarm Optimization (VEPSO) as a novel, co-evolutionary multi-objective variant of the popular PSOA, to achieve a specified strength with minimizing weight and total cost of the composite component, under different failure criteria (such as the Tsai-Wu, maximum stress and failure mechanism based failure criteria). The comparison between these criteria showed that the failure mechanism produced better results.

2.4. Ant Colony Optimization (ACO)

Ant Colony Optimization (ACO) is a paradigm for designing meta-heuristic algorithms for combinatorial optimization problems. The essential part of ACO algorithms is the combination of *a priori* information about the structure of a promising solution with *a posteriori* information about the structure from previously obtained good solutions.

In each social insect colony, there is a system or plan to follow by all individuals and the overall groups seem to be well organized. ACO is based on the cooperative behavior of real ant colonies, which are able to find the shortest path from their nest to a food source. The method was developed by Dorigo and his associates in the early 1990s (Dorigo *et al*., 1996).

In general, the ACO approach attempts to solve an optimization problem by repeating the following two steps:

a) candidate solutions are constructed using a pheromone model, that is, a probability distribution over the solution space;

b) the candidate solutions are used to modify the pheromone values in a way that is deemed to bias future sampling toward high quality solutions.

This algorithm depends on the swarm intelligence to solve complicated problems.

The ACO has been used successfully in the optimization of fiber composite structure. Regarding laminated structures, the first study was done by Yang *et al*., (2006). Abachizadeh & Tahani, (2009), used ant colony optimization to maximize the fundamental frequency and to minimize the cost of symmetric hybrid laminates. Lay-up design of laminated panels, for maximization of buckling load with strength constraints, was studied by Aymerich & Serra, (2008). A simply supported composite laminate was investigated for optimal stacking sequence under strength and buckling constraints by Bloomfield *et al*., (2010). Koide *et al*., (2013), describes the development and application based on ACO, in order to find the optimal stacking sequence of laminated composite plates. For a hybrid laminated plate with mixed domain of solution, including fiber angles as continuous variables and number of surface (or core) layers as integer discrete variables, Abachizadeh *et al*., (2010), showed that an extension of ACO for continuous domains leads to very good results. A modified ACO with novel operators called *multi-city-layer ant colony algorithm* is also proposed by Wang *et al*., (2010), exhibiting this method as more robust and efficient comparing with GAs for buckling load maximization of a rectangular laminate.

Table 1 contains different examples of the optimization and parametric studies with the results as a benefit for the fiber composite structures design (Awad, 2012).

Table 1

Comparison of the Optimization Methods (after Awad, 2012)

Method / Parametric studies	Genetic Algorithm (GA)	Simulating Annealing Method (SAM)	Particle Swarm Optimization Algorithm (PSOA)	Ant Colony Optimization (ACO)
Objective	multi-objective	multi-objective	multi-objective	multi-objective
Probability	✓	✓	x	✓
Free derivative	✓	✓	✓	✓
Solution cost	low in parallel optimization	low	less than GAs for single objective	moderate
Optimum solution remark	global	multiple global optimum	– global –convergence difficulties	good performance
Overall ranking	high	moderate	high	moderate

In recent years, a large number of algorithms, based on the swarm intelligence, has been proposed by various researchers. The Artificial Bee Colony (ABC) algorithm is one of most popular stochastic, swarm based algorithms proposed by Karaboga, (2005), inspired from the foraging behavior of honey bees. Swarm intelligence algorithms are a new range of computational algorithms that have emerged from the behavior of social insects.

Based on the ABC algorithm a new version of Vector Evaluated Artificial Bee Colony (VEABC) algorithm for discrete variables has been developed and implemented successfully for the multiple objective design optimization of composites (Omkar *et al.*, 2011).

3. Conclusion

Optimal design of laminated composite structures is challenging due to the possibility to locally adapt the material system to the mechanical situation. Trying to find solution to optimization problems, many researchers have been looking for inspiration in the world of insects or in the evolution of human being. Their work mimic certain characteristics and behaviors of biological entities, leading to various optimization techniques such as Genetic Algorithm (GA), Simulated Annealing Method (SAM), Particle Swarm Optimization Algorithm (PSOA), Ant Colony Optimization (ACO) and Artificial Bee Colony (ABC) algorithm. These algorithms, with their stochastic means, are well equipped to handle difficult optimization problems. Of these, GA has been a very popular tool for the combinatorial design optimization of composite structures.

Stochastic methods are more appropriate for composite lay-up design, because of their capabilities of handling a mixture of continuous and discrete variables, finding the global optimum of a multi-modal objective function, and working with a population of solutions. These methods usually have low rate of convergence, which is also a problem dependent factor. Consequently, comparing stochastic methods is unfeasible because their heuristic nature make them strongly dependent on the problem. Until now, GA has been the most popular method, with SAM ranked the second.

During the last two decades, there has been a growing interest in using GA techniques for the optimum design of structures made of laminated composites. Most effort in this field has been devoted to optimizing the stacking sequence of laminates.

The application of optimization methods offers many benefits in the design of composite civil structures.

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PREZENTARE GENERALĂ A METODELOR DE OPTIMIZARE ÎN STRUCTURI COMPOZITE PENTRU APLICAȚII ÎN INGINERIA CIVILĂ

(Rezumat)

Un compozit laminat este de obicei adaptat nevoilor proiectării privind alegerea grosimii, numărului şi orientării straturilor. Pentru a obține cele mai bune rezultate, au fost dezvoltate tehnici de optimizare. Potențialele avantaje ale laminatelor compozite au făcut ca mulți cercetători să pună în aplicare diferiți algoritmi, cu scopul de a obține cea mai potrivită structură pentru o situație dată. În ultimii ani au fost dezvoltate câteva metode de optimizare, diferite conceptual de tehnicile tradiționale de programare matematică. Aceste metode sunt etichetate ca metode moderne sau netradiționale de optimizare. Cele mai multe dintre aceste metode sunt bazate pe anumite caracteristici şi comportamentul roiurilor de insecte. În lucrare se analizează unele dintre cele mai populare metode de optimizare, utilizate în proiectarea structurilor compozite folosite în construcții civile: Genetic Algorithm (GA), Simulated Annealing Method (SAM), Particle Swarm Optimization Algorithm (PSOA) şi Ant Colony Optimization (ACO). Studiile publicate subliniază importanța acestor metode de optimizare a structurilor compozite şi provocarea de a le dezvolta pentru a obține performațe în domeniu.