UNITECH 2021 GABROVO

INTERNATIONAL SCIENTIFIC CONFERENCE
19-20 November 2021, GABROVO

THE HEURISTIC ALGORITHMS USED IN THE OPTIMIZATION OF LAMINATED COMPOSITE STRUCTURES: A REVIEW

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Abstract

The composite materials can be combined at macro level in order to obtain the appropriate properties, or to create a new property of two or more materials in a single material. Since they have high strength/weight (specific strength) and stiffness/weight (specific modulus) ratios, and can be designed with different and desired mechanical properties, they are especially used in many of the engineering fields such as aerospace industry, land and sea transportation where the lightness and strength parameters are important. In the design of laminated composite structures, many design parameters such as the number of layers, different fiber and matrix materials, geometric properties and loading types are taken into consideration. Therefore, the optimization of these structures becomes a complex problem, and it will be inevitable to use a heuristic algorithm to solve this problem. The heuristic algorithms are commonly used in the optimization of laminated composite structures. These algorithms converge rapidly, and are very effective in the optimization problems where there are too many design parameters and the exact solution cannot be found easily. In this study, the common heuristic algorithms used in the optimization of laminated composite structures are introduced.

Keywords: Composite materials, laminated structures, optimization, heuristic algorithms

1. INTRODUCTION

Composite materials are generally preferred in the load – carrying elements such as beams, plates and shells, and they are usually constructed of different materials and number of layers. Since the composite materials have high strength/weight (specific strength) and stiffness/weight (specific modulus) ratios, they are widely used in the laminated structures. The optimization of laminated structures can be defined as the determination of the stacking sequences, fiber orientation angles and layer thicknesses in order to fulfill a certain design goal. During the optimization process, many restrictive parameters should be taken into account such as the mechanical and geometrical properties of material, manufacturing methods and cost. Thus, the design can be optimized in terms of the strength, rigidity, stability and cost. In the structural optimization, the major element to be considered is to obtain the most appropriate structural configuration that can provide the targeted values. Depending on the type of the optimization problem, the targeted objectives of the structure may vary, thus, various parameters must be taken into consideration in order to achieve these targeted values. Although there are many optimization methods, the heuristic algorithms are widely used in the optimization of the laminated composite structures. They do not guarantee the exact solution in the optimization problem, but a set of solution which is close to the exact solution is guaranteed. The heuristic algorithms generate reliable results in the optimization problems where there are too many design parameters. The main objective of this study is to introduce the common heuristic algorithms used in the optimization of laminated composite structures.

2. THE OPTIMIZATION OF LAMINATED COMPOSITE STRUCTURES

Depending on the type of problem, different parameters can be taken into consideration in the optimization of laminated composite structures. For example; in the aerospace industry, the design with minimum weight can be the optimum solution, whereas the design with minimum cost can be the optimum in other areas. However, in some cases, instead of minimum cost and weight, the design with maximum strength can be called as the optimum solution. The stacking sequences, fiber orientation angles, number and thickness of layers are the design parameters in the laminated composite structures. These parameters are generally optimized in order to maximize or minimize the targeted values in the optimization problem. For example, these parameters can be optimized in order to find out the minimum in-plane stresses or displacements to prevent the failure or collapse within the structure. In the same manner, the optimization can be performed in order to find out the maximum fundamental natural frequency or critical buckling load in order to prevent resonance or deformation in the structure. In Figure 1, a schematic design of a laminated composite structure is presented. The coordinate axes ($x-$, $y-$ and $z-$) are placed in the mid-surface of the structure. θ, t and n correspond to the fiber orientation angle, layer thickness and number, respectively.

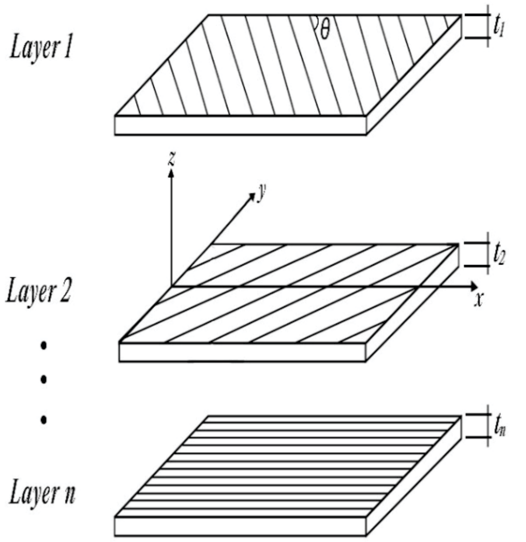

Figure 1. A schematic design of a laminated composite structure

The optimization process can be performed depending on different design parameters. For instance; in the stacking sequence optimization of a three layered composite beam with a fiber orientation angle changing with an increment of 10° between 0° and 90°, there can be 1000 possible solutions. As it is obvious, increasing the number of layers or decreasing the increment of fiber orientation angle will bring about too many solutions. The optimization problem will become more complex, and the use of classical methods will cause a high processing time and decrease the convergence rate to the optimum solution. Thus, depending on the number of too many possible solutions, the use of a heuristic algorithm in the optimization problem will be inevitable.

3. THE HEURISTIC ALGORITHMS USED IN THE OPTIMIZATION OF LAMINATED COMPOSITE STRUCTURES

The heuristic algorithms are developed depending on the natural sciences such as biology, physics and chemistry. They have convergence properties, and are very effective in the optimization problems where the exact solutions cannot be found easily, and the trial and error method is insufficient in terms of the time and cost. The common heuristic algorithms used in the laminated composite structures can be classified into the following way:

3.1. Particle Swarm Algorithm (PSA)

PSA is a heuristic optimization method inspired by the individuals in a swarm, and generally depends on the herd intelligence and approximate position of the individuals in the herd, namely the particles. In this method, the fitness function is used to estimate the approximate position of an individual to the targeted result. The algorithm deals with a population of particles where each particle represents a possible solution to the problem. The flowchart of PSA is summarized as follows:

Step 1: Start.
Step 2: Set the parameters and starting position of the swarm.
Step 3: Calculate the fitness value of each particle.
Step 4: Update the “pbest (personal best)” and “gbest (globalbest)” values.
Step 5: Calculate the rate of change of the particles. Check the new positions.
Step 6: Has the stopping criteria been obtained?

Step 7: If the answer is "Yes", go to Step 8. If "No", go back to Step 3.
Step 8: Finish.

Kathiravan and Ganguli [1] discussed the optimum design of a composite beam subjected to the strength constraints using both gradient-based and PSA. Layer angles are used as the design variables, and various initial design and loading situations are considered. It is mentioned that while PSO gives the best designs globally, the gradient-based method can also be used in conjunction with appropriate initial designs to yield reliable results. Manan et al. [2] investigated the vibration of a simple rectangular wing by use of different layer orientations with PSA. Moussavian and Jafari [3] calculated the optimal values of the effective parameters on the stress distribution around the semi-square cut using different optimization algorithms, and examined the performance of these algorithms. To achieve this goal, they used the analytical results of symmetrical laminated composite plates with square cross-sections, and obtained better results with PSA.

3.2. Genetic Algorithm (GA)

GA is a permutation-based optimization method. It works in a similar way to the evolutionary process observed in nature. Once the fitness function is determined, the initial population is created and the fitness value of each individual is calculated. Then the individuals are ranked from minimum to maximum, or vice versa, with respect to their fitness values. After the initial population is created and the individuals are ranked, the genetic operators such as reproduction, cross-over and mutation are applied at each step of the algorithm in order to increase the quality of the individuals in population. Genetic algorithm performs a global search to solve the optimization problem, but not a local one. The flowchart of GA is given as follows:

Step 1: Start.
Step 2: Determine the fitness function.
Step 3: Create the initial population and determine the fitness value of each individual.
Step 4: Perform reproduction.
Step 5: Perform cross-over.
Step 6: Perform mutation.
Step 7: Has the stopping criteria been obtained? If the answer is "Yes", go to Step 10. If "No", go to Step 8.
Step 8: Check the fitness values of new individuals.
Step 9: Check the new population and continue from Step 4.
Step 10: Finish.

Karaçam and Tımarcı [4] investigated the applicability of GA to the static analysis of laminated beams constructed of composite materials. They compared the results with the ones in the literature, and examined the performance of the algorithm. Vosoughi et al. [5] introduced a combined method for obtaining the maximum fundamental frequency of thick-layer composites by finding the fiber orientation. The main equations were derived based on the high-order shear deformation theory, and the finite element method was used to parse the equations. GA was used to find the optimum fiber orientation of the thick plate. The applicability and usability of the method is demonstrated by solving different examples. Farsadi et al. [6] optimized the natural frequencies of the curvilinear fiber composite and conical cylindrical panels with GA. Then, they investigated the nonlinear frequency behaviors according to the optimum curved fiber angles. Moradi et al. [7] proposed a new strategy to find the optimum stacking sequence of a laminated composite structure to achieve the maximum buckling loads. For this purpose, buckling analysis was performed with ABAQUS. In the optimization process, PSA and GA were introduced.

3.3. Simulated Annealing Algorithm (SAA)

SAA is a heuristic optimization method which is especially efficient in the solution of discrete and less continuous optimization problems. The main purpose of this algorithm is to obtain an overall improvement for the problem which has a specific solution. The algorithm is especially preferred in the optimization problems that cannot be solved by use of mathematical models. The principle of SAA is generally similar to the iron annealing process. The main parameters can be assumed as the initial temperature, cooling coefficient, target temperature and number of iterations as in the annealing process. The flowchart of SAA is given as follows:

Step 1: Start.
Step 2: Run the solution.
Step 3: Is it accepted? If the answer is “Yes”, go to Step 4. If “No”, go to Step 5.
Step 4: Update the existing solution.
Step 5: Is there a temperature variation? If the answer is “Yes”, go to Step 7. If “No”, go to Step 6.
Step 6: Generate the new solution and go back to Step 1.
Step 7: Lower the temperature.
Step 8: Has the stopping criteria been obtained? If the answer is “Yes”, go to Step 10. If “No”, go to Step 9.
Step 9: Go back to Step 6.
Step 10: Finish.

Erdal and Sönmez [8] presented a method to find out the global optimum designs for two-dimensional composite structures subjected to the certain in-plane static loads where the critical failure mode is buckled. The buckling load capacity of laminated structure was maximized by use of an improved SAA. Javidrad and Nouri [9] investigated the optimum stacking sequence to obtain the required hardness properties. The number of layers and angles of the fibers were chosen as the design variables. The optimum layers were then obtained by minimizing a cost function consisting of the calculated effective stiffness properties. The minimization problem was solved using a modified simulated annealing algorithm. A cooling procedure in which the temperature-drop was based on the objective function, was considered in the algorithm. It was concluded that the proposed simulated annealing algorithm had more reliable results with a faster processing time.

3.4. Artificial Bee Colony Algorithm (ABCA)

ABCA is a heuristic optimization method which is based on the foraging behavior of the bees in a swarm. It is based on the unique honey bee behavior when they use for searching the nectar sources. The locations of the nectar sources correspond to the possible solutions of the optimization problem, and the nectar amounts of the sources correspond to the quality, that is, the suitability of the solutions related to those sources. Therefore, ABCA aims to locate the source with the most nectar. The flowchart of ABCA is presented as follows:

Step 1: Start.
Step 2: Generate the initial nectar source positions.
Step 3: Calculate the nectar amounts.
Step 4: Check the neighbor sources for the attendant bees.
Step 5: Calculate the nectar amounts.
Step 6: Create selection.
Step 7: Have all of the onlooker bees been deployed? If the answer is “Yes”, go to Step 10. If “No”, go to Step 8.
Step 8: Check the neighbor of the bee chosen by the onlooker bee.
Step 9: Build up the nectar amount and continue to Step 6.
Step 10: Memorize the position of the best source.
Step 11: Check the resources to drop.
Step 12: Generate the new resources to replace with the dropped resources.
Step 13: Has the stopping criteria been obtained? If the answer is “Yes”, go to Step 14. If “No”, go to Step 4.
Step 14: Finish.

Omkar et al. [10] presented a method/model for multi-objective design optimization of laminated composite structures based on the vector evaluated artificial bee colony algorithm (VEABCA). They formulated the problem with multiple objectives by minimizing the weight and overall cost of the composite structure to achieve a given specific strength. Topal and Öztürk [11] optimized the stacking sequences of simply supported asymmetric laminated composite structures choosing the critical buckling load as objective functions. The optimization process has been performed for different aspect ratios, number of layers, and loading conditions. Apalak et al. [12] searched the applicability of ABCA to the layer optimization. They maximized the lowest fundamental frequency of symmetric laminated composite plates subjected to any combination of three classical boundary conditions. The finite element method was used to calculate the natural frequencies of the laminated composite with various stacking sequences. Esmaeeli et al. [13] optimized the fiber angles to maximize the elastic constants of in-plane strains. Then, by combining ABCA and various multi-objective optimization methods, the optimum fiber angles and corresponding co-optimized constants were determined.

3.5. Ant Colony Algorithm (ACA)

ACA is inspired from the ant colonies in the nature. It consists of the artificial ants that have a repeating structure by updating the artificial pheromone traces. While the algorithm is running, the pheromone traces updated by the ants generate information to find the good, namely, the optimum solution, and this information is updated at each iteration. The flowchart of ACA is given as follows:

Step 1: Start.
Step 2: Set the initial pheromone values.
Step 3: Place the ants in each colony randomly (Each ant completes its iteration by selecting the next colony, based on the local search probability given in the equation.).
Step 4: Calculate the length of the paths taken by each ant and update the pheromone locally.
Step 5: Calculate the best solution and update the global pheromone.
Step 6: Has the stopping criteria been obtained? If the answer is “Yes”, go to Step 7. If “No”, go to Step 2.
Step 7: Finish.

Aymerich and Serra [14] examined the application of ACA to the laminated composites to maximize the buckling load with strength constraints, and compared the performance and robustness of the algorithm with the others. Wang et al. [15] investigated the optimum design of T-shaped symmetric composite structures. By use of ACA, the maximum buckling load optimization was carried out. The stacking sequence, thickness and height were chosen as the design variables. Abachizadeh et al. [16] used ACA to determine the optimum stacking sequence for the maximum frequency and minimum cost for laminated composite structures constructed of graphite/epoxy and glass/epoxy material for 8, 16 and 28 layers. Sebaey et al. [17] investigated the benefits of dispersed layers over conventional layers in terms of stiffness, buckling resistance and strength for two types of loading conditions in structural applications. The study was conducted to select the most appropriate failure criterion among the others with ACA. Koide and Luersen [18] used different methods to find out the response of laminated cylindrical shell structures constructed of composite material. For this reason, the optimum stacking sequences are considered in order to maximize the fundamental frequency, and compared with the results obtained by Abaqus. Koide et al. [19] used ACA to find the optimum stacking sequences of laminated composite plates. The algorithm was evaluated on four samples for symmetrical and balanced stacking sequences, and the results were compared with the other optimization methods.

4. RESULTS AND DISCUSSIONS

The use of heuristic algorithms in the composite structures has increased in recent years. In this study, the common heuristic algorithms have been introduced, and following conclusions have been achieved:

- The heuristic algorithms can be used for problems where the exact solution cannot be defined, and should be interpreted more easily by the user in order to find an exact solution in the searching space.

- In the laminated composite structures modelled with specific mathematical equations, some parameters can be neglected depending on the usage area and limitations. In addition, the use of inappropriate parameters during the design process may lead to undesirable results in the structure.

- During the optimization process, the relationship between the solution quality and the processing time of the algorithm should be checked. Otherwise, the processing time may increase, and it may take a long time to find the optimum solution. Therefore, the algorithms may deviate from their original purpose of use.

- Depending on the type of problem, the heuristic algorithm used in the design and analysis of laminated composite structures should be well determined. When compared with the classical optimization methods, the heuristic algorithms will converge to the optimum results faster and easier when the appropriate variables and objective functions are selected.

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