Design and optimization of fiber composites

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14.1 Introduction

In engineering, design, and optimization processes are very important issues to establish sustainable engineering systems. Compared to isotropic materials, it is necessary to deal with more complicated mathematical models that address the material anisotropy for fiber-reinforced composites. Due to the unique characteristics of fiber-reinforced composite materials such as different directional properties, interlaminar stresses, less notch sensitivity, and having positive and negative coefficients of thermal expansion, they require more material constants for characterization of the hygrothermomechanical responses. Therefore, the design process of composites for the effort required or the benefit desired has to be systematic, which includes innovative approaches to synthesize alternative solutions. In this regard, the main goal of all such attempt is relevant to reach minimizing the effort required or to maximize the desired benefit. Conceptually, "best design" for fiber-reinforced composites refers to optimization of the structural material. The process is quite different from the design approaches that are traditionally used for metals such as aluminum and steel. For example, by only material point of view, the designer has to choose the reinforcement type (short, long, particulate, micro, nano, etc.), the matrix, and also the process for curing in terms of performance and cost. Hence, in other words, the optimization of fiber-reinforced composites often means having (i) the lowest weight with limitations on the stiffness properties, (ii) the minimum cost with prescribed strength limits, or (iii) the maximum stiffness with prescribed resources.

In recent years, thanks to advanced computers and commercial programs, optimization methods are rapidly being used in many engineering design applications such as manufacturing processes, aerospace structures, and automotive. Moreover, optimization methods, coupled with modern tools of CAD (computer-aided design), are also being used to provide major improvement in the structural design of engineering systems [1,2].

In the formulation of the design problems, engineers utilize the design variables that directly change the properties of the material. Hence, best design (or optimization) of the considered structures has acquired a meaning. So as to develop better structural performance of the fiber-reinforced composites and satisfy the conditions of a specific design case, the thermophysical properties of the material can be tailored in addition to structural dimensions Gurdal et al. [1]. However, some of the

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configurations designed to tailor the material properties are not manufactural even if there are many different production methods to obtain a composite part or a structure. Therefore, engineers do indeed work under some limited conditions that configurations are manufactural, thereby limiting the performance gains, which can be established through the use of fiber composites. Because of their anisotropic nature, unfortunately, it might not possible to find an efficient composite structural design that satisfies all the prescribed conditions by only sizing the cross-sectional areas and member thicknesses. In these cases, determining (i) the stacking sequence of a laminate, (ii) the material properties of each layers, and (iii) the number of layers becomes more of an issue for fiber composites.

14.2 Structural design

Only some specific structural design criteria, loading cases, components, and units have been carried out in almost all studies on the optimization of fiber-reinforced composite structures such as pressure vessels, bars, and disks. It should be noted that the structural optimization of a fiber-reinforced composite under different limitations qualifies as a fundamental problem in both structural design and strength analysis [3]. Structural design also ought to have the possibility of being extended to deal with anisotropic nature of fiber composites. It would be great if the following design requirements are valid for the fiber-reinforced composite structures: (i) high strength, (ii) long fatigue life, (iii) high stiffness, (iv) specified amounts of energy absorption, (v) light weight, (vi) low cost, (vii) dimensional stability, (viii) manufacturability, (ix) high natural frequency, and (x) high fracture toughness. However, in some circumstances, only one requirement is utilized to describe required properties. Generally, real-life applications of the engineering design problems on fiber composites are very complicated, and also two or more design requirements such as low weight-low cost, stiffness-low weight-low cost, and high fracture toughness-low weight-low cost have to be considered simultaneously. Hence, the designer has become some advantages and disadvantages when the number of inputs of a structural engineering system is high. For instance, it is effective to study with many inputs (design variables), since the engineers need to control the behavior of the fiber-reinforced composite structures satisfying the design constraints. However, it is very difficult to select and reach the correct (optimum) design variables and their corresponding values. It can be established only if it is based upon a systematic and/or mathematical approach. In these cases, design optimization of fiber composites becomes a suitable tool, and therefore, different solution methodologies should be taken into account.

14.3 Material selection

The general performance of an engineering system is limited by the physical properties of its material. Therefore, one of the most important tasks in engineering is to describe the factors and procedures to select the appropriate material for a specific structural application. After the material-selection step of an engineering component, the process follows two interrelated problems: (i) specifying the shape of the unit and (ii) choosing a manufacturing process [4]. Performance of the fiber-reinforced composites depends on combination of physical properties, and then, the best material can be selected by maximizing one or more performance indices. Three fundamental questions are often helpful to select a composite material:

1. What are the factors governing the selection of the fiber (carbon, glass, kevlar, etc.)?
2. What are the factors essential for selection of the matrix (epoxy or polyester polypropylene)?
3. What are the overall factors about selection of the fiber-reinforced composite material?

The designer performs a series of selection stages. On each stage, a pair of fiber and matrix properties is specified.

14.3.1 *Fiber selection factors*

Fiber selection process for composites has to be attuned to design requirements of the engineering applications. Most important issues are (i) strength or stiffness, (ii) hygrothermomechanical properties, (iii) the thickness of a ply/availability of tow size, (iv) ply flexibility, (v) sizing and surface treatments, (vi) wetting, bonding, and material compatibility, and (vii) cost and availability.

Appropriate selection of the fiber and matrix will produce a fiber-reinforced composite system that (i) satisfies the conditions on design, (ii) facilitates manufacturing processes, and (iii) minimizes program risks (cost and schedule).

14.3.2 *Matrix selection factors*

The selection of appropriate matrix for a fiber-reinforced composite material is crucial and also involves many factors since the matrix links in all properties of a two-phase fiber composite material. The main considerations include (i) ability of the matrix to wet the fiber, (ii) fiber sizing compatibility, (iii) ease of processing, (iv) toxicity and health concerns, (v) cost and availability, (vi) prepeg handling characteristics, (vii) laminate quality, (viii) environmental resistance, (ix) moisture absorption, (x) composite glass transition temperature, (xi) tooling expansion, (xii) density, (xiii) flow characteristics, (xiv) tensile strength, (xv) diffusivity, and (xvi) microcracking. In Table 14.1, the principle properties of matrix materials: polymer, metal, carbon, and ceramic are given.

Table 14.1 **Elements for matrix selection**

	Rating of matrix materials			
Elements for selection	**Worst**	**Applicable**	**Good**	**Best**
Laminate quality	Ceramic	Carbon	Metal	Polymer
Fiber wetting	Ceramic	Metal	Carbon	Polymer
Processing ease	Ceramic	Metal	Carbon	Polymer
Strain-to-failure	Ceramic	Carbon	Metal	Polymer
Environmental resistance	Polymer	Metal	Carbon	Ceramic
Density	Metal	Ceramic	Carbon	Polymer
Cost	Metal	Carbon	Ceramic	Polymer

Based on Jones RM. Mechanics of composite materials. 2nd ed. Philadelphia: Taylor & Francis; 1999.

14.4 Optimization

Essentially, optimization of a structure can be defined as finding the best design or elite designs by minimizing the specified single objective or multiobjectives that satisfy all the constraints. Single-objective and multiobjective optimizations are the main approaches used in structural design problems. In single-objective approach, an optimization problem consists of a single-objective function, constraints, and bounds. However, the design of practical composite structures often requires the maximization or minimization of multiple, often conflicting, two or more objectives, simultaneously [5]. In such a case, multiobjective formulation is used, and a set of solutions are obtained with a different trade-off called Pareto optimality. Only one solution is to be chosen from the set of solutions for practical engineering usage. There is no such thing as the best solution with respect to all objectives in multiobjective optimization. Optimization techniques can be classified as traditional and nontraditional. Traditional optimization techniques, such as constrained variation and Lagrange multipliers, are analytic and find the optimum solution of only continuous and differentiable functions. Since composite design problems are very complex and have discrete search spaces, the traditional optimization techniques cannot be used in this area. In these cases, the use of stochastic optimization methods such as particle swarm (PS), genetic algorithms (GA), generalized pattern search algorithm (GPSA), and simulated annealing (SA) are appropriate. In composite laminate design problems, derivative calculations or their approximations are impossible to obtain or often costly. Therefore, stochastic search methods have also the advantage of requiring no gradient information of the objective functions and the constraints [6]. In the fiber-reinforced composite design and optimization studies, fiber orientation angles, and thickness are considered as the main design variables. In some optimization problems, lamina thicknesses [7–11] and/or fiber orientation angles [12,13] are also given as design variables [55].

14.4.1 Single-objective optimization

A standard mathematical formulation of the single-objective optimization consists of an objective function, equality and/or inequality constraints, and design:

$$\begin{aligned}
&\text{minimize} && f(\theta_1,\theta_2,\ldots,\theta_n) \\
&\text{such that} && g_i(\theta_1,\theta_2,\ldots,\theta_n)\geq 0 \quad i=1,2,\ldots,r \\
& && p_j(\theta_1,\theta_2,\ldots,\theta_n)=0 \quad j=1,2,\ldots,m
\end{aligned}$$

where f is the objective function, $\theta_1, \theta_2, \ldots, \theta_n$ are the design variables, and g and p are the constraints of the problem. In composite design and optimization problems, mass, stiffness, displacements, residual stresses, thickness, vibration frequencies, buckling loads, and cost are used as objective functions Gurdal et al. [1].

14.4.2 Multiobjective optimization

A multiobjective optimization problem can be stated as follows:

$$\begin{array}{ll}\text{minimize} & f_1(\theta_1,\theta_2,\ldots,\theta_n), f_2(\theta_1,\theta_2,\ldots,\theta_n),\ldots,f_t(\theta_1,\theta_2,\ldots,\theta_n)\\ \text{such that} & g_i(\theta_1,\theta_2,\ldots,\theta_n)\geq 0 \quad i=1,2,\ldots,r\\ & p_j(\theta_1,\theta_2,\ldots,\theta_n)=0 \quad j=1,2,\ldots,m\end{array}$$

where $f_1, f_2, \ldots, f_t$ represent the objective functions to be minimized simultaneously. The main difficulties in multiobjective optimization problems are to minimize the distance of the generated solutions to the Pareto set and to maximize the diversity of the developed Pareto set. Detailed analysis of multiobjective optimization can be found in Deb [14].

14.4.3 Stochastic optimization algorithms

Stochastic optimization methods are optimization algorithms based on probabilistic elements, either in the objective function with the constraints or in the algorithm itself or both of them. GA, particle swarm optimization (PSO), ant colony optimization (ACO), SA, tabu search, harmony search, and GPSA are examples of the stochastic search techniques used in engineering applications. In composite laminate design problems, derivative calculations or their approximations are impossible to obtain or is often costly. Therefore, stochastic search methods have the advantage of requiring no gradient information of the objective functions and the constraints. In the following subsections, steps of the widely used algorithms are briefly overviewed.

14.4.4 Genetic algorithm

The GA is a stochastic optimization and search technique that allows obtaining alternative solutions for some of the complex engineering problems such as increasing composite strength and developing dimensionally stable and lightweight structures. GA method utilizes the principles of genetics and natural selection. This method is simple to understand and uses three simple operators: selection, crossover, and mutation. GA always considers a population of solutions instead of a single solution at each of iteration. It has some advantages in parallelism and robustness of GA. It also improves the chance of finding the global optimum point and helps to avoid local stationary point. However, GA is not guaranteed to find the global optimum solution to a problem. GA has been applied to the design of a variety of composite structures ranging from simple rectangular plates to complex geometries Aydin and Artem [5].

14.4.5 Generalized pattern search algorithm

GPSA has been defined for derivative-free unconstrained optimization of functions by Torczon [15] and later extended to take nonlinear constrained optimization problems into account. GPSA is a direct search method, which determines a sequence of points that approach the optimal point. Each of iteration is divided into two phases: the search phase and the poll phase. In the search phase, the objective function is evaluated at a finite number of points on a mesh. The main task of the search phase is to find a new point that has a lower objective function value than the best current solution, which is called the incumbent. In the poll phase, the objective function is evaluated at the neighboring mesh points, so as to see whether a lower objective function value can be obtained. GPSA has some collection of vectors that form the pattern and has two commonly used positive basis sets; the maximal basis with $2N$ vectors and the minimal basis with $N+1$ vectors Aydin and Artem [5].

14.4.6 Simulated annealing

SA is a random search technique, and it is based on the simulation of thermal annealing of heated solids to achieve the minimum function value in a minimization problem. It is possible to solve mixed integer, discrete, or continuous optimization problems by using SA. In this algorithm, a new point is randomly generated at each iteration, and the algorithm stops when any of the stopping criteria are satisfied. The distance of the new point from the current point or the extent of the search is based on Boltzmann's probability distribution. The distribution implies the energy of a system in thermal equilibrium at temperature T.

Boltzmann's probability distribution can be written in the following form [2,5]:

$$P(E) = e^{-E/kT} \tag{14.1}$$

where $P(E)$ represents the probability of achieving the energy level E, k is the Boltzmann's constant, and T is temperature.

SA algorithm has the following steps:

1. Start with an initial vector x_1 and assign a high temperature value to the function.
2. Generate a new design point randomly and find the difference in function values.
3. Determine whether the new point is better or worse than the current point.
4. If the value of a randomly generated number is larger than $e^{-\Delta E/kT}$, accept the point x_{i+1}.
5. If the point x_{i+1} is rejected, then the algorithm generates a new design point x_{i+1} randomly.

However, it should be noted that the algorithm accepts a worse point based on acceptance probability [2].

14.4.7 Particle swarm optimization

The PSO algorithm resembles the character of social beings such as swarm of ants and flock of birds. PSO algorithm searches the solution and at the same moment, agents (swarming search points) share their information or feedbacks among themselves. When we compare PSO's certain features with other frequently used stochastic search algorithms in optimization problems such as GA, PSO is proved to be more effective. In most of these problems, PSO is also demonstrated to have tremendous computational abilities. Moreover, it does not follow any gradient types of information. In a brief computation time, PSO can adapt universal and local exploration and exploitation abilities by incorporating a well-organized and also flexible mechanism. This method efficiently overcomes large and complex search spaces. For example, to understand clearly about the mechanism as model, it can be given a similar behavior from a flock of bird. When a food (target; maximum of the objective function) is located by one bird, this information is instantly passed to all other birds. Then, those birds head toward the target but not directly. While this happens, it should be considered that all birds have independent behavior with having their past memory. While Kennedy and Eberhart proposed the PSO algorithm in Ref. [16], its effectiveness is reported in an experimental study, which is about using the PSO algorithm for the optimal design of ply arrangement, by Kovacs et al. [17].

14.4.8 Differential evolution methods

Differential evolution (DE) is a stochastic optimization and search technique, which permits to gain alternative solutions for some of the complex engineering problems such as increasing frequency, frequency separation, and obtaining lightweight design. DE includes four main stages: initialization, mutation, crossover, and selection. The algorithm is checked by three parameters: scaling factor, crossover, and population size. The detailed description of the DE can be found in Ref. [56]. As in GA method, differential evolution methods (DEM) always considers a population of solutions instead of a single solution at each of iteration. Although the DEM is computationally expensive, it is relatively robust and efficient in finding global optimum and to avoid local minimum irrespective of initial points. However, DEM is not guaranteed to find the global optimum solution to a problem. DEM has been implemented to the design of a sort of fiber composite structures ranging from simple rectangular plates to complex geometries.

14.4.9 Ant colony optimization

Dorigo and Gambardella [18] presented the study on the solution of the traveling salesman problem by artificial ant colony. Furthermore, this algorithm has been able to be adapted on many integrated problems such as job-shop scheduling and vehicle routing [19,20]. ACO, which was developed by Dorigo and his collaborators in 1992, is directly based on real ant colonies that have the ability to find the shortest route from their nest to source of food without thrusting their visual cues but pheromone information. Pheromone of each ant is used by next ant following the same route by the probability of the trail of this chemical clue. By increasing the usage of same route, trails of pheromone raises on the route, which attracts more ants to follow same way. However, the pheromone deposited on the route evaporates in time. This character is described in the algorithm as three fundamental operations, which are known as "state transition," "local updating," and "global updating," and regulates to build a solution in a constructive approach. Graph representations are frequently used in most problems solved with ACO method. For this process, values that are defined for each couple of elements or location of elements in the solution define the pheromone function. As a result, all or some of these elements form the final solution for the problem.

14.4.10 Topology (layout) optimization of fiber reinforced composites

In structural systems and constitutes, the selection of the best configuration is handled by layout or topology optimization. Topology optimization is the simultaneous selection of "the optimal layout," which is spatial sequence of members and joints, "geometry" being the location of joints and "cross-sectional dimensions" being sizing of a structure. Ideal layouts are supported on the use of isotropic materials being inside of the framework of classical black-white or 0-1 structures. Initial improvements in studies for topology optimization were about employment of composite material, which is described as interpolation of void and whole material. These early developments were based on a theoretical work leading an apprehension, which is the issue of existence of solutions resolved by increasing in extent of the design space to consist of relaxed designs, for the form of composites [57].

In order to submit composites as a part of the solution method in layout design, it is required to mind with a number of branches of material science and especially the methods for computing the effective material parameters of composites. After, it should be dealt with the limits on the possible behavior of effective material and straightly gives the knowledge gathered on the optimal use of local material properties. Therefore, this layout design named as the *homogenization approach* generates the principals for many studies. Individuating between the use of the methodology being generally as a tool for interpolation of properties and studies where existence of solutions means central aspect can be performed.

One can be sure that the importance/value of designing with composites as a study area is quite high. This design includes such variables that are the optimum orientation and the optimal layup of each ply of an orthotropic material. If one desires to find the optimal design, which can include any material, it is possible to select to work with an entirely free parametrization of the stiffness tensor.

Being orthotropic (anisotropic) materials, one can generally enter the angle of rotation of the directions of orthotropy as a design parameter in terms of desired transformation formulas for frame rotations in the design of composites. One should know that the density of the material is a function of many design variables describing the geometry of the holes at the microlevel. Moreover, it is also necessary to optimize the variables. Therefore, complexity of the problem will increase depending on spatial point or mesh element. Then, in order to create optimal structure, one can expect to find density values of 0 and 1 in major areas. In addition to these, one is also able to find detailed information about layout optimization for fiber-reinforced composite material structures in the reference being Bendsøe et al. [21].

In Table 14.2, a short review on design optimization of fiber-reinforced composite structures is given, including optimization methods, fiber types, and composites.

Table 14.2 Examples of engineering optimization problems for fiber-reinforced composite structures

Authors	Optimization problem	Optimization methods	Composite material	Fiber type
Aydin and Artem [5]	Design the stacking sequence of the laminated composites that have low coefficient of thermal expansion and high elastic moduli	Generalized pattern search, simulated annealing (SA), and genetic algorithm (GA)	Carbon-epoxy	Unidirectional long
Kaveh et al. [22]	Minimum thickness design of laminated composite plates under in plain loading	Charged system search algorithm	Graphite-epoxy	Unidirectional long
Koide and Luersen [23]	Maximization of fundamental frequency of laminated composite cylindrical shells	Ant colony	Graphite-epoxy	Unidirectional long
Walker et al. [24]	Design of laminated cylindrical shells for maximum torsional and axial buckling loads	Golden section	T300/5208 graphite epoxy	Unidirectional long
Lopatin and Morozov [25]	Buckling of the composite orthotropic clamped-clamped cylindrical shell loaded by transverse inertia forces	Finite element analysis by using Galerkin method	Glass fiber-reinforced polymeric composite	Unidirectional long
Mingfa et al. [26]	Design and structural optimization of specifically shaped composite tanks with complex loading conditions	Adaptive SA algorithm	Values are given without material name	Unidirectional long
Jafari and Rohani [27]	Optimization of perforated composite plates under tensile stress	GA	1. CE9000 glass-epoxy 2. Woven glass-epoxy 3. Plywood 4. Carbon-epoxy	1. Thin long 2. Woven 3. Thin long 4. Thin long

Continued

Table 14.2 Continued

Authors	**Optimization problem**	**Optimization methods**	**Composite material**	**Fiber type**
Li and Chandrashekhar [28]	Structural optimization of laminated composite hydrokinetic turbine blades	Particle swarm optimization (PSO)	E-glass/epoxy as facesheet and shear web with foam core (core is ignored for optimization process)	Long continuous
Manne and Tsai [29]	Optimization of minimum weight, layup, and thickness taper for quadrilateral plates having cutouts	Nelder-Mead	Graphite-epoxy *ASIH3501*	Unidirectional long
Hu and Fis [30]	Optimization of nonlinear composite materials and structures at multiple scales	Ant colony	Noncrimp fabric composite	Unidirectional long fiber
Aydin et al. [6]	Design and optimization of dimensionally stable composites	Efficient global optimization	Carbon/epoxy	Unidirectional long
Tabakov [31]	Design optimization of the pressure vessel subjected to Tsai-Hill failure criterion	Big Bang-Big Crunch algorithm	T300/5208 graphite epoxy	Unidirectional long
Deveci et al. [32]	Buckling optimization of composite plates under Puck failure criterion	Hybrid genetic and trust-region-reflective algorithms	Given values without material name	Unidirectional long
Thompson et al. [33]	Optimization of fiber-reinforced polymer composite bridge deck panels	Reliability-based optimization	Glass-epoxy	Unidirectional long
Madhusudhanan and Giri [34]	Design optimization of hybrid composite leaf spring	Firefly algorithm	1. Steel 2. Jute/E-glass/epoxy 65Si7	Woven E-glass
Lakshmi and Rao [35]	Optimization of fundamental frequency for 64-ply hybrid laminate plate	Multipopulation-based harmony search algorithm	Design 1: Graphite-epoxy Design 2: Graphite and	Unidirectional long

		with dynamic interaction of population	glass-epoxy as hybrid composite	
Paia et al. [36]	Optimization of the stacking sequence of a laminate for buckling response, matrix cracking, and strength requirements	Tabu search	Graphite-epoxy	Unidirectional long
Rao and Arvind [37]	**(a)** Thermal buckling optimization of laminated composite plates **(b)** Optimization of hybrid laminate composite panels for weight and cost with frequency and buckling constraints	Scatter search	**(a)** Graphite-epoxy (AS/3501) **(b)** Graphite-epoxy and glass-epoxy (generic S-glass/ epoxy)	Unidirectional long
Fang and Springer [38]	Optimizing symmetrical fiber-reinforced composite laminates such that the weight is minimum and the Tsai-Wu strength failure criterion is satisfied	Monte Carlo	E-glass/epoxy composite	Unidirectional long
Chernivov et al. [39]	Optimum postimpact vibration control of an electrically conductive carbon fiber-reinforced composite plate subjected to an uncertain, or stochastic, impact load	Two-stage stochastic partial differential equation-constrained optimization methodology	Carbon fiber-reinforced composite	Thin long unidirectional fiber
Duy et al. [40]	Lightweight design optimization of laminated composite plates subjected to frequency constraints	Adaptive elitist differential evolution algorithm	Carbon-bismaleimide	Unidirectional long
Liu and Paavola [41]	Lightweight design of composite laminated structure with frequency constraint	Gradient projection algorithm	Carbon-bismaleimide	Unidirectional long

Continued

Table 14.2 Continued

Authors	Optimization problem	Optimization methods	Composite material	Fiber type
Vosoughi and Nikoo [42]	Multiobjective optimization of laminated composite plates for maximum natural frequency and thermal buckling temperature.	New hybrid differential quadrature, nondominated sorting genetic algorithm II, and Young bargaining model algorithm	Graphite-epoxy	Unidirectional long
Hemmatian et al. [43]	Multiobjective optimization of hybrid laminates for minimum weight and cost with fundamental frequency constraint	Elitist ant system	Graphite-epoxy Glass-epoxy	Unidirectional long
Omkar et al. [44]	Multiobjective optimization of laminated composite plates for minimum cost and weight	MPI-based parallel synchronous vector Evaluated PSO	Carbon-epoxy	Unidirectional long
Jiang et al. [45]	Design the stacking sequence of the laminated composites for maximum stiffness	Interval number programming method	Glass-epoxy	Unidirectional long
Jing et al. [46]	Stacking sequence optimization of composite laminates for maximum buckling load	Permutation search algorithm	Graphite-epoxy	Unidirectional long
Liu et al. [47]	Design the stacking sequence of the laminated composites for maximum buckling load	Permutation GA	Graphite-epoxy	Unidirectional long
Chang et al. [48]	Stacking sequence optimization of composite laminate	Permutation discrete PSO		Unidirectional long
Fakhrabadi et al. [49]	Multiobjective optimization of laminated composite plates for minimum cost and weight under different failure criteria	Discrete shuffled frog-leaping algorithm	Carbon-epoxy	Unidirectional long

Shin [50]	Design of a stiffened laminated plate for maximum buckling load	Homotopy method	Graphite-epoxy	Unidirectional long
Kalantari et al. [51]	A multiobjective robust optimization hybrid composites for minimize cost and weight under flexural loading	NSGA-II	Carbon-epoxy Glass-epoxy	Unidirectional long
Topal [52]	Multiobjective optimization of laminated cylindrical shells to maximize a weighted sum of the frequency and buckling load under external load	Modified feasible direction method	Graphite-epoxy	Unidirectional long
Omkar et al. [53,54]	Multiobjective optimization of laminated composite plates for minimum cost and weight under different failure criteria	Vector-evaluated artificial bee colony	Carbon-epoxy	Woven E-glass

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