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Probabilistic Optimization of Laminated Composites Considering Both Ply Failure and Delamination Based on PSO and FEM*

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Abstract: Reliability-based design is one of major strategies for cost-effective designs under uncertainties in either engineering designs or manufacturing processes. This paper presents an approach integrating particle swarm optimization algorithm (PSO) and finite element method (FEM) into the reliability-based design optimization (RBDO). The total weight of the laminate was taken as the objective function, the fiber directional angle and thickness ratio as the design variables. Both in-plane damage and delamination were taken into account. The result shows that the value of object function using the proposed method is much greater than those without considering delamination in literature and demonstrate that the proposed method produces more conservative result.

Key words: reliability-based design optimization; interlaminar stresses; particle swarm optimization; finite element method; failure criterion

Introduction

In recent decades, laminated composites have been applied in many fields, i.e., aerospace, aviation, construction, automobile, machinery, and other fields for the excellent performance. Composite laminate is a multi-layered structure with low interlaminar intensity, whose bearing capacity often decreases with interlaminar failure. Therefore, the potential performance of composite laminate can not be fully exploited. Pipes and Pagno[1] used the finite-difference calculation of free-edge stress fields to give the results of stress distribution, which indicated that free edge effect occurs everywhere along free edges. Due to the singularity of interlaminar stresses in practice[2,3], delamination failure near the free edges of laminate often occurs before the strength limit predicted by the classic laminate theory (CLT) is reached. In order to obtain reliable design in engineering practice, the three-dimensional stresses near the free edges should be considered[4,5]. Moreover, reliability-based design is one of major strategies for cost-effective designs under uncertainties in either engineering designs or manufacturing processes[6,7]. Recently, several theories under uncertainties were developed for engineering[8-11].

In this paper, we propose a novel method that integrates particle swarm optimization algorithm (PSO) and finite element method (FEM) into the reliability-based design optimization (RBDO), which is applied to laminated composites. Both in-plane failure criterion and interlaminar failure criterion are taken into account when calculating the reliability of the laminates. PSO can solve continuous and discrete global optimization problem efficiently and accurately for a high-dimensional and non-smooth objective function[12].

1 Reliability-Based Design Optimization

A general reliability-based design optimization

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problem with only random variables and deterministic design variables can be stated as

$$\begin{aligned} &\underset{\boldsymbol{d}}{\text{Minimize}}\ f(\boldsymbol{d}, \boldsymbol{X}), \\ &\text{s.t. } g_i(\boldsymbol{d}, \boldsymbol{X}) \geqslant b_i, \quad i = 1, 2, \ldots, p; \\ &\Pr(z_j(\boldsymbol{d}, \boldsymbol{X}) \geqslant 0) \geqslant R_j,\ j = 1, 2, \ldots, q \end{aligned} \tag{1}$$

where f denotes the design objective function, $\boldsymbol{d}$ is the vector of deterministic design variables or control factors, $\boldsymbol{X}$ is a vector of random variables, $g_i(\boldsymbol{X})$ is the i-th general constraint function, p is the number of the general constraints, Pr is the reliability constraint function, q is the number of the reliability constraints, R_j is the j-th prescribed safe probability limit.

This paper combines PSO and FEM and divides the RBDO of composite laminates into three nested modules: optimization module, the module of reliability analysis, and the module of stress analysis. The whole process of the method is shown in Fig. 1. The optimization module is performed by PSO, while the module of stress analysis by FEM. The reliability in the module of reliability analysis is evaluated by the iterative method. Three modules are nested each other by transferring corresponding variables and parameters. In each optimization cycle, reliability analysis and stress analysis are required. The stresses obtained by stress analysis are substituted into the performance function in the module of reliability analysis. The module reliability of reliability analysis behaves as a constraint of the optimization module. Since the stresses are obtained by FEM, the reliability evaluation will be more accurate. Three modules will be illustrated in detail in the following sections.

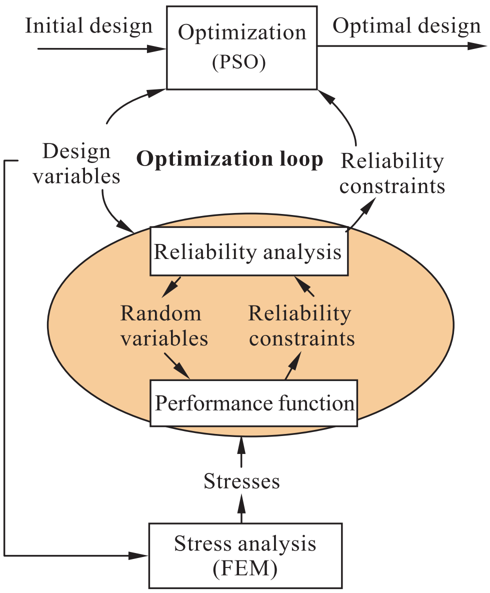

Fig. 1 The process of the proposed method

1.1 PSO algorithm

The PSO is a heuristic global optimization search technique based on community intelligence. Each particle represents a potential solution for the optimization design problem and has a position represented by a position vector. Initially, particle swarms are initialized with random position values and random initial velocities and then they are accelerated towards their previously best positions (the solutions attained by each particle) and their best global position (the solution attained by the whole swarm). Each particle updates its own velocity and position according to the following two formulas.

$$v_i^{(k+1)} = wv_i^{(k)} + c_1 \text{rand}_1(\text{pbest}_i - x_i^{(k)}) + c_2 \text{rand}_2(\text{gbest}_i - x_i^{(k)}) \tag{2}$$

$$x_i^{(k+1)} = x_i^{(k)} + v_i^{(k+1)} \tag{3}$$

where i denotes the i-th particle, k denotes the k-th iteration, v_i is the fly velocity of the i-th particle, x_i is the current position of the i-th particle, c_1 and c_2 are the acceleration constants (c_1=c_2=2.05), rand_1 and rand_2 are uniformly distributed random numbers in the interval [0, 1], w is the inertia weight, pbest_i is the the individual's i-th best position found so far and gbest is the global best position attained by the swarm found so far.

This process is iterated until a minimum error is achieved or a set number of times are achieved.

1.2 Reliability analysis

When only random variables and design variables are involved, the structural reliability is defined as

$$R = \Pr[z(\boldsymbol{d}, \boldsymbol{X}) \geqslant 0] = \int_{z(\boldsymbol{d}, \boldsymbol{X}) \geqslant 0} f_{\boldsymbol{X}}(\boldsymbol{X}) \mathrm{d}\boldsymbol{X} \tag{4}$$

where z is a performance function (also called limit-state function) and f_X is the joint probability density function (pdf) of the random variables. Once the original random vector $\boldsymbol{X}$ is transformed into a set of random vector $\boldsymbol{U}$ whose elements follow a standard normal distribution, then the reliability is rewritten as

$$R = \Pr[z(\boldsymbol{d}, \boldsymbol{X}) \geqslant 0] = \int_{z(\boldsymbol{d}, \boldsymbol{U}) \geqslant 0} \mathrm{f}_U(\boldsymbol{U}) \mathrm{d}\boldsymbol{U} = \Phi(\beta) \tag{5}$$

where f_U is the joint pdf of $\boldsymbol{U}$, $\Phi()$ is the cumulative distribution function (cdf) of the standard normal