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Optimization of laminated composite plates for maximizing buckling load using improved differential evolution and smoothed finite element method

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ABSTRACT

This paper proposes a novel numerical optimization procedure with mixed integer and continuous design variables for optimal design of laminated composite plates subjected to buckling loads. In the present optimization problem, the objective function is to maximize the buckling load factor. The design variables are fibre orientation angles and thickness of layers, in which the fibre orientation angles are integer variables and thickness are continuous variables. The constraints include the limitation of variables and the total thickness of the plate. For analyzing the buckling behavior of laminated composite plates, a recently proposed smoothed finite element method named the cell-based smoothed discrete shear gap method (CS-DSG3) is employed. For solving the current optimization problems which contain both integer and continuous variables, an improved different evolution algorithm, named mixed-variable different evolution (mDE) is proposed. In the mDE, the mutation and selection phases of the original DE are replaced by an adaptive mutation mechanism and an elitist selection technique, respectively. These improvements not only help balance effectively the global and local search abilities of the DE, but also help deal with integer and continuous design variables. The reliability and effectiveness of the proposed optimization procedure are investigated through some numerical examples for optimal design of laminated composite plates with 2, 3, 4 and 10 layers subjected to buckling loads. Additionally, the influence of different loading and boundary conditions on the optimal solution is also investigated.

1. Introduction

Due to various advantageous properties such as high strength-to-weight ratio, high stiffness-to-weight ratio and flexibility in design, laminated composite plates have been increasingly used in various engineering disciplines like automotive industries, civil infrastructures, and aerospace structures. In many applications, the buckling phenomenon which is critically dangerous to structural components can be observed [1]. Therefore, buckling analysis of laminated composite plates has attracted considerable attention from researchers around the world. Many different methods have been proposed to address this issue. For example, Sherbourne & Pandey [2] investigated the accuracy and convergence of the differential quadrature method (DQM) for buckling analyses of composite plates. Kam and Chang [3] used a simple shear deformable finite element method based on the first-order shear deformation plate theory. Wang et al. [4] ultilized a meshless approach based on the reproducing kernel particle method. Chakrabarti & Sheikh [5] employed a six-node triangular element plate based on higher order shear deformation theory. Huang & Li [6] used the moving least square differential quadrature (MLSDQ) method based on the first-order shear deformation plate theory. Ni et al. [1] ultilized both the higher-order shear deformation plate theory and two-dimensional Ritz displacement functions for an arbitrary edge support. Liu et al. [7] presented a mesh-free radial basis function based on third-order shear deformation plate theory. Ferreira et al. [8] employed wavelets. Nguyen et al. [9] proposed a smoothed quadrilateral element (MISQ24). Recently, the NURB-based isogeometric finite element method was also used for buckling analysis of laminated composite plates [10,11].

Although a variety of numerical methods for analyzing buckling behavior of the laminated composite plates have been reported, it

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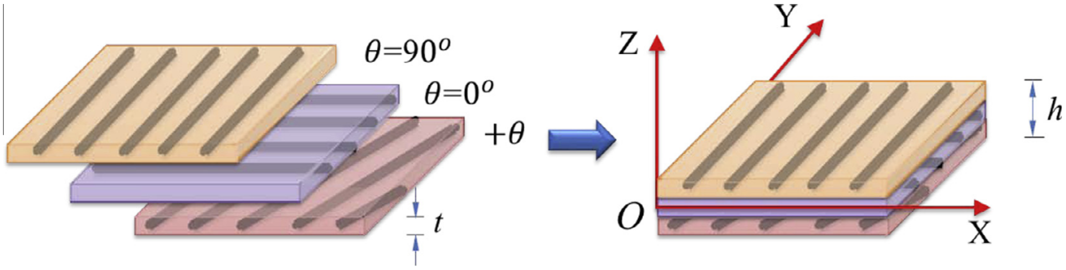

Fig. 1. Model of a laminated composite plate.

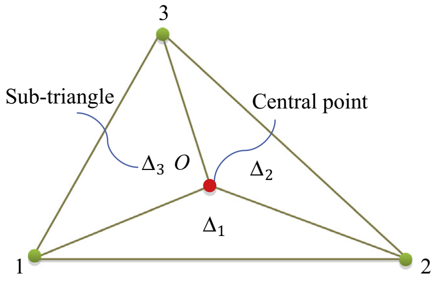

Fig. 2. Three sub-triangles (Δ_1, Δ_2 and Δ_3) created from the triangle 1–2–3 in the CS-DSG3 by connecting the central point O to three field nodes 1–3.

can be seen that the usage of three-node triangular Mindlin plate elements is somewhat still limited. This paper hence extends a recently proposed smoothed Mindlin plate element namely cell-based smoothed discrete shear gap method (CS-DSG3) [12] for analyzing the buckling behavior of composite plates. In the CS-DSG3, each triangular element is divided into three sub-triangles, and in each sub-triangle, the stabilized DSG3 is employed to compute the strains. Then the cell-based strain smoothing technique on whole the triangular element is used to smooth the strains on these three sub-triangles. The numerical results showed that the CS-DSG3 is free of shear locking and achieves the high accuracy compared to others existing elements in the literature. It has been successfully extended to analyze various plate and shell problems such as flat shells [13], stiffened plates [14], FGM plates [15], piezoelectricity plates [16], composite and sandwich plates [17], plates resting on viscoelastic foundation subjected to moving loads [18,19], cracked plates and shells [20,21], and some other extensions [22–24].

It is known that the variation of fibre orientation angles, thickness as well as stacking sequence can help achieve the required mechanical properties, such as in-plane, flexural and buckling behavior of composite laminates [25]. As a result, seeking the optimal values of the fibre orientation angles and thickness of layers for maximizing buckling load has also received much interest from researchers. Some first studies based on classical approaches and gradient-based methods can be found in Refs. [26–35]. However, these methods often give the optimum solution which depends too much on the initial point provided by users. Thus, if the initial point is not selected well, especially for the highly-nonlinear optimization problems with many design variables, it is very hard to obtain the global optimum solution. Moreover, since these methods usually use gradient information for searching the solution, they will encounter troubles in dealing with the optimization problems with mixed integer and continuous design variables. In recent years, many population-based methods such as genetic algorithm (GA) [36–38], ant colony optimization (ACO) [39] have also been developed to overcome limitations of the gradient-based methods. These methods directly use the information of the objective function and constraints for searching without using gradient information. In addition, they have a high probability to obtain a global solution and can easily solve the mixed variable optimization problems. However, they often possess a big restriction related to high computational cost, especially when the buckling behavior of composite plates is analyzed by numerical methods (e.g. finite element method). Therefore, it is really necessary to further develop the global optimization methods which can obtain the highly-accurate optimum solution with lower computational cost.

Among population-based optimization methods, the differential evolution (DE) firstly introduced by Storn and Price 1997 [40], is one of the most popular algorithms. The DE demonstrated good performance in solving many different engineering problems with continuous design variables such as communication [41], pattern recognition [42], mechanical engineering [43–48], structural health monitoring [49,50], artificial neural network training [42,51]. Compared to the GA and ACO, the DE outperforms both them in two aspects including the quality of the solution and convergence rate [52,53]. Nevertheless so far, it has not yet been considered for buckling optimization of the composite plates. In addition, similar to many other population-based optimization algorithms, the computational cost of the DE for finding the global solution is still high, especially for real-world problems in which the cost for evaluating the objective function and constraints is expensive [54].

Based on the above considerations, in this paper, we propose a novel numerical optimization procedure with mixed integer and continuous design variables for optimal design of laminated composite plates subjected to buckling loads. In this procedure, for analyzing the buckling behavior of laminated composite plates, the cell-based smoothed discrete shear gap method (CS-DSG3) is employed. For searching the optimal solution, an improved

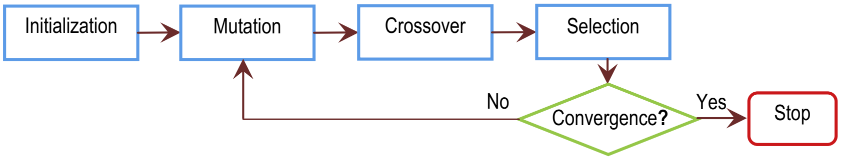

Fig. 3. Flowchart of the DE algorithm.