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Optimal design of composite sandwich structures by considering multiple structure cases

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ABSTRACT

Acting as primary and secondary structures, sandwich components made of laminated composite face sheets are widely applied in aerospace structures. For simultaneous optimization designs of both stacking sequences of the face sheets and the core thickness, the design problem for composite sandwich structures becomes a combinatorial one by involving both discrete and continuous design variables, for orientation angles of the face-sheet laminate plies are constrained to discrete permissible designs while the core thickness is continuous. Additionally, practical structures like solar arrays are required to satisfy given constraints under multiple structure cases, which involve multiple finite element models and make the problem more complicated. In this study, for optimal designs of composite sandwich structures under multiple structure cases, an optimization model is firstly established by involving both discrete and continuous variables meanwhile integrating all structural cases into a single problem formulation. A stacking sequence optimization method proposed previously by the authors which utilizes two-level approximations and a genetic algorithm is extended to solve the above problem, and an optimization framework is developed by interfacing the improved method with the finite element software MSC.Patran/Nastran. Numerical applications are conducted to demonstrate the feasibility of this optimization system.

1. Introduction

With advanced features such as high strength-to-weight and stiffness-to-weight ratios, sandwich panels composed of fiber-reinforced plastic face sheets and foams or honeycomb core materials are widely used in aerospace as primary and secondary structures or for structures intrinsic to subsystems such as solar arrays and reflectors [1]. Optimal designs of the face sheets (or the skins) and/or the core becomes indispensable to make full use of the composite properties [2,3], and the considered variables can be the thickness and orientation angles of the skins as well as the core thickness, the core density and the geometry of the unit cell, etc., which makes the design problem of sandwich structures much more cumbersome than that of a classical monolithic structure [4,5]. In an easier and faster way, some research works on pure face sheet optimizations [6–8] or determining exclusively the optimum thickness of both the skins and the core meanwhile keeping other parameters constant [9,10] were reported. By exploring more design space to find the true global optimal configuration of the sandwich structures, a general two-level optimization strategy was proposed in [4,5,11] which involved different scales: the meso-scale for both the unit cell of the core and the constitutive layer of the laminated skins and the macro-scale for the whole panel. In the present work, the considered design variables involve the face-sheet stacking sequences and the core thickness. By considering manufacture constraints, the orientations in the face sheets are constrained to a list of discrete permissible designs, i.e. 0°, ±45° and 90°, and the ply thickness are assumed as fixed. The optimization for the face sheets becomes an integer programming problem and can be categorized as laminate stacking sequence optimizations, and relevant optimization techniques can be found in the review articles [12,13]. Since the design for both the lay-up of face sheets and the core thickness may affect each other, the core thickness can be regarded as a continuous variable at the same time to improve the structure performance. Consequently, the simultaneous optimization of the face-sheet stacking sequences and the core thickness becomes a nonlinear problem involving both discrete and continuous variables.

Genetic algorithms (GAs) are quite well suited to tackle this problem with mixed variables, and many near optimal solutions can be produced as options for designers. Besides GA, other evolutionary algorithms like the simulated annealing algorithm [14] can be feasible alternatives. However, as each individual or member

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needs to be evaluated during the process, considerable function evaluations are consumed in such algorithms [15], and that makes them unsuitable for practical large-scale problems. In order to improve the efficiency, some techniques are incorporated in these evolutionary algorithms, like the parallel computing [16] and approximation concepts. Kodiyalam et al. [1] implemented the genetic search method in a design optimization system for satellite structures, and a linear least-squares approximation was introduced to minimize the computational effort, but it was found that for large-scale problems the number of function evaluations remains high [16]. Gantovnik et al. [17] used a binary tree in GA to avoid a replicated evaluation of the same design alternatives and the computational effort could be reduced to some extent. Meanwhile, a spline approximation was adopted to involve both discrete and continuous variables. However, it is also restricted due to the fact that for each set of the discrete variables a sufficient number of design points for each continuous variable is required [18]. Kaletta et al. [18] presented several methods to enhance the efficiency of such evolutionary algorithms, including a combined application of different types of evolutionary operators, an adaptation of the optimization parameters itself as well as an approximate evaluation of design configurations, and numerical results showed that the required structural analyses could be reduced largely. From these works, it can be seen that evolutionary algorithms like GAs combined with approximation methods can be a viable option to significantly reduce the computational costs.

For real-world engineering problems, the designer has to consider an optimization of the system under multiple structure cases. The concept of multiple structure cases refers to a structural system having different working states or conditions to complete different tasks. For instance, when a variable-sweep aircraft [19] takes off or flies at high speeds, it is subjected to two working conditions, i.e. low and high sweep angles, for the wings; another case is the flexible attachment in a spacecraft, like the solar array panels and reflectors, which have compacted and deployed states related to the launch stage and the orbital working status, respectively. The mechanical requirements under the considered structure cases are different, indicating different design constraints, while the structure system is still composed of the same components, implying the same design variables. Structural optimization by taking into account multiple structure cases consists in designing a given structure (that can take different geometrical configurations under prescribed working conditions) by satisfying simultaneously all constraints under each structure case. Compared with the single-structure-case optimization, multiple finite element (FE) models should be involved at each iteration step for all structural cases, if the finite element based method is employed. Meanwhile, it can be seen that optimizations under multiple structure cases are quite different from the usual optimizations considering multiple load cases, and they have drawn high demands in optimization strategies. Some research works on multiple-structure-case optimization designs can be found in [20,21], where only the continuous sizing variables were optimally determined. In this study, the multiple-structure-case design problem for sandwich structures is considered by involving both discrete and continuous variables.

In recent studies, a two-level multipoint approximation method combined with GA was proposed by the authors [22,23] for stacking sequence optimizations. The structural response analyses required in the GA were replaced with a series of sequential approximation problems; in the meantime, accurate structural analyses were only conducted on iteration points to improve the quality of the approximate function, which is substantially different from the response surface methods that need lots of accurate structural analyses to construct a response surface before the optimization starts. Accordingly, computational costs are significantly reduced, and several near optimal alternatives can be provided for the designers. Later, this method was extended for simultaneous optimizations of stacking sequences in composite laminates and cross-sectional dimensions in other structural components [24], where only pure laminate panels could be considered, but it could not be applied to the design problem of composite sandwich panels when the core thickness is also taken as design variables. Additionally, this method has no capability in dealing with problems for composite sandwich structures under multiple structure cases.

In the present work, the main objective is to establish an optimization framework for optimal designs of composite sandwich structures under multiple structure cases by extending the previously proposed two-level approximation method. The optimization model is firstly built by involving both face-sheet stacking sequence variables and core thickness variables. By considering multiple structure cases, the problems established under all structural cases are integrated into a single problem formulation. To solve this problem, a first-level approximate problem expressed with a branched multi-point approximate (BMA) function is adopted to make the original problem explicit by including both types of variables. The series of the first-level approximate problems are then optimized with a GA, in which the gene is correspondingly updated to represent the continuous core thickness variables. Individual fitness calculations are achieved after optimizing the ply thicknesses as well as the core thicknesses in a second-level approximate problem. With MSC.Patran/Nastran, an optimization framework is established by combining the optimizer with the finite element software. A simply supported sandwich panel is firstly designed to test the effectiveness of this framework in dealing with composite sandwich structure optimizations under single structure case. Afterwards, a practical solar array structure made of composite sandwich panels considering two structural cases, i.e. deployed and compacted states, is optimized to verify the feasibility of the proposed approach when considering multiple structure cases.

2. Problem formulation

To achieve the simultaneous optimization design of the face-sheet stacking sequences and the core thickness of a composite sandwich structure, the problem model is firstly established by considering two types of variables. For the stacking sequence optimization, an initial lay-up design with arbitrary plies and permissible orientations, such as 0°, ±45° and 90°, is firstly given. Based on this given lay-up, discrete 0/1 variables corresponding to each layer are used to determine the existence/absence of each ply in this initial design. Meanwhile, a continuous ply thickness variable related to each layer is also created. This initial stacking sequence can be regarded as the concept of the ground structure proposed in the truss topology optimization [25]. By determining the existence and absence of truss elements in the given ground structure, the optimal truss layout can be obtained. Back to the present study, some plies might be deleted from the initial lay-up during the discrete-variable optimization, and some ply thicknesses of the remaining plies might be increased after the continuous-variable optimization, which is similar to the truss topology optimization. With such treatment, the optimal stacking sequences can be obtained for the face sheets.

For the core thickness, a continuous variable linked with this core is firstly created, and a constant discrete variable, which is kept unchanged at a value of 1, is set up for this core thickness. Such treatment guarantees the number of discrete variables is equal to that of continuous variables.

Furthermore, the optimization under multiple structure cases is considered. A structurally efficient design can be defined as the one