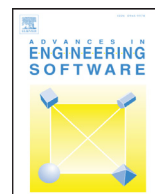




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Research paper

Fast cylinder variable-stiffness design by using Kriging-based hybrid aggressive space mapping method

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ABSTRACT

In this study, a surrogate assisted hybrid aggressive space mapping method is suggested to optimize buckling loads of cylinder variable stiffness composites made by fiber steering. Compared with other popular space mapping algorithms, both of surrogate and coarse FE model are integrated to obtain the coarse FE model-based solution. Moreover, the accuracy of surrogate can be enhanced by the sample points evaluated by the fine FE model. Therefore, the suggested method is easy to converge. After optimization by using the suggested algorithm, the buckling load of the variable stiffness cylinder optimized by the method has 43.12% improvement than the constant stiffness cylinder and 32.12% improvement than the quasi-isotropic cylinder, respectively. Therefore, it suggests that the suggested method has potential capability to handle complicated design for composites and can be extended to other complicated disciplines.

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1. Introduction

The structural benefits of the Variable-Stiffness (VS) laminate are achieved by tailoring material properties in directions which are easier to carry loads within the laminates. Compared with the classical Constant Stiffness (CS), the VS laminate is capable to exploit the full potential of composite materials by extending the design style and might be attributed to an additional capacity to redistribute loads from the highly loaded regions [1–5]. Moreover, fiber steering capability of a VS laminate has been proved to be feasible in structural performance improvement of composite structures. However, there are still several design and manufacturing challenges which need to be addressed to reach its full potential in mechanical characteristics, such as buckling loads. Therefore, the effects of fiber steering in improving the buckling loads of plates and cylindrical shells have been extensively studied. Hyer et al. [6] improved the buckling resistance of a plate with a circular hole using a curvilinear fiber path. Lund and Stegmann [7] examined two benchmark problems, a single-layer and a 16-layer supported plates, and they concluded that the buckling load can be increased by up to 44% when using a VS design compared with the CS one. Setoodeh et al. [5,8] pointed out that the VS design could increase the buckling load of a single-layer and a balanced symmetric square VS plates up to 166% and 67%, respectively. Ijsselemden et al. [9] studied various loading and boundary conditions on balanced the symmetric square VS plates. It demonstrated

improvements more than 100% in buckling loads of a VS design compared to a CS design. Blom et al. [10] improved the bending induced buckling load of a composite cylinder up to 17% with respect to its CS counterpart. Khani et al. [11] proposed a two-step optimization framework to separate the theoretical and manufacturing issues in the VS design. To further exploit the advantages of VS laminates, it is suitable to systematically formulate a design problem based on an optimization framework. Since the fiber orientation continuously changes within the laminate of VS design, the evaluations of structural property by Finite Element (FE) simulation are often quite time-consuming [12,13]. To save the computational cost, designers may consider using surrogate or a metamodel assisted optimization [14–23]. As a result, the surrogate could be substituted real evaluation procedure to significantly save the computational time. Some kinds of Surrogate Assisted Optimization methods (SAOs) have been employed to VS design recently. Alhajmad and Gürdal [24] used Simulated-Annealing Algorithm (SA) to find the optimal fiber paths within each ply of the laminate for maximum load carrying capacity and buckling capacity. Vandervelde and Milani [25] employed the SAO to improve the free vibration behavior for the design of a multiple zone composite wing. However, simultaneous optimization for the buckling load and the in-plane stiffness of a VS laminate ignored the presence of defects, i.e. gaps and overlaps [10]. Therefore, Arian Nik et al. [31] used the Kriging surrogate to maximize the buckling load and the in-plane stiffness of a VS laminate with embedded defects. Moreover, Huang et al. [26,27], He et al. [28] and Wang et al. [29,30] used a fast solver, reanalysis to improve the efficiency of design procedure. Even so, with the increase of the number of plies, the number of

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design variables should increase correspondingly. Furthermore, if the microscale problem is considered [32], the computational cost should be significantly improved. Moreover, consider curse of dimensionality, the computational cost is still expensive. Because the majority of computational consuming is the simulation-based evaluation, if the computational cost of each simulation evaluations can be dramatically reduced, the efficiency of an optimization procedure should be improved correspondingly. Therefore, an efficient optimization toolkit, Space Mapping(SM) algorithm is introduced and applied to the VS design in this work.

The SM algorithm proposed by Bandler et al. [33] was firstly applied to the circuit optimization. To reduce the computational cost of accurate evaluations for fine model, it aims at associating the fine model with the coarse model(less accurate but fast). The combination may utilize both an efficient and good accurate method to the final solution. Although the SM applies mainly in electromagnetics initially [34–37], it could be used in other multidiscipline [38,39] because the fundamental principles of SM are general. With the development of SM algorithm, several approaches have been put forward to utilize SM algorithms in engineering modeling, such as Trust Region Aggressive Space Mapping algorithm (TRASMS) [34], Hybrid Aggressive Space Mapping (HASMS) algorithm [35], Generalized SM (GSM), Implicit SM (ISM) [40] and Manifold Mapping (MM) [41,42]. Compared with direct optimization method, the efficiency of SMs can be significantly improved. However, with the increase of complexity of physical models, even the computational costs of coarse model are also expensive. Therefore, the most of recently developed SM algorithms are based on the surrogate modeling approaches. However, it is difficult for most of surrogate modeling approaches to construct high fidelity models for complicated physical problems, especially for high dimensional problem. Therefore, an alternative surrogate assisted SM is suggested. The framework of the suggested SM is based on the HASMS. The surrogate is based on the coarse model and applied to optimize the optimal solution in each iteration. In the each iteration, the surrogate should be updated by using sample points evaluated by the model. Obviously, the surrogate model improves the efficiency of the suggested algorithm and the fine model can guarantee the quality of the surrogate. We hope to be able to use the suggested algorithm to complete the VS design efficiently.

The rest of paper is organized as follows. In Section 1, problem description of the VS is given. Basic theories of SMs used in this study are introduced. To compare the performances of ASM and HASMS, some test functions are tested in Section 4. To save the computational cost, a surrogate assisted HASMS is suggested and applied to the VS design.

2. Problem description of the variable stiffness

2.1. Variable stiffness properties definition

In an early study [43,44], in-plane analysis of rectangular panels made of balanced symmetric angle-ply laminates possesses a linear variation of a pair of fiber angle $[\pm \theta(x)]_s$ along one of axes (i.e. x in this study), and a panel has been also studied under axial compression. The linear variation along the x axis, which is assumed to be centered along the length a of a panel, implied:

$$\theta(x) = \frac{2(T_1 - T_0)}{a} |x| + T_0 \quad (1)$$

where T_0 denotes the fiber orientation angle at a panel center, $x=0$. T_1 denotes the fiber orientation angle at the panel ends, $x=\pm a$.

The fiber reference path associated with unidirectional fiber orientation variation given in Eq. (1) is demonstrated by the solid line in Fig. 1. Although the fiber orientation angle varies along a

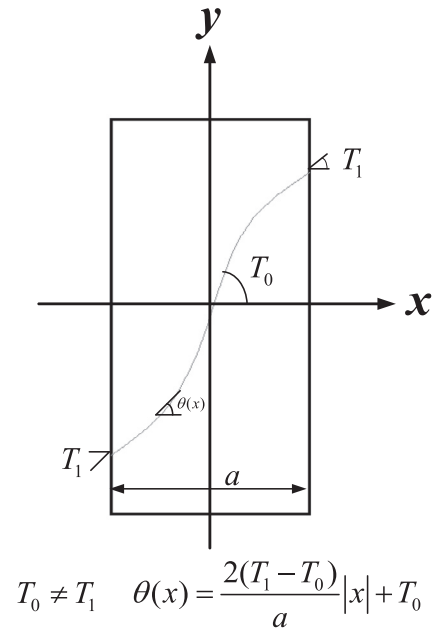


Fig. 1. A curvilinear fiber path that varies linearly along x -axis.

single axis, x , assuming that the fiber orientation at other points in the design space is obtained by shifting this basic path in a direction perpendicular to the axis x , the actual fiber orientation change on the plane x - y is now a function of one coordinate direction, $\theta(x)$. Three-parameter fiber path description (Eq. (1)) is not the only way to describe curvilinear fiber paths, but it is a simple way to be adopted. Moreover, other descriptions are also available, some details can be found in the literature [43]. To clearly introduce the effect of the stiffness variation on the response of a laminate, the theoretical unidirectional definition is used so that we can concentrate on the response mechanisms of variable stiffness laminate concept without considering manufacturing feasibility. Assuming plane stress conditions for the individual layer and using Classical Lamination Theory (CLT) for fiber-reinforced composites, the constitutive relations for a laminated element are:

$$\mathbf{N} = \mathbf{A}\boldsymbol{\varepsilon}^0 + \mathbf{B}\boldsymbol{\kappa} \quad (2)$$

$$\mathbf{M} = \mathbf{B}^T \boldsymbol{\varepsilon}^0 + \mathbf{D}\boldsymbol{\kappa} \quad (3)$$

$\mathbf{N}^T = \{\mathbf{N}_x, \mathbf{N}_y, \mathbf{N}_{xy}\}$ and $\mathbf{M}^T = \{\mathbf{M}_x, \mathbf{M}_y, \mathbf{M}_{xy}\}$ are membrane force and bending moment vectors, respectively. $\boldsymbol{\varepsilon}^0$ is the in-plane strain vector. $\boldsymbol{\kappa}$ is the bending strain vector. The coefficients of elastic stiffness matrices are given by

$$\mathbf{A}_{ij} = \sum_{k=1}^N \bar{\mathbf{Q}}_{ij}^{(k)} (z_k - z_{k-1}) \quad (4)$$

$$\mathbf{B}_{ij} = \frac{1}{2} \sum_{k=1}^N \bar{\mathbf{Q}}_{ij}^{(k)} (z_k^2 - z_{k-1}^2) \quad (5)$$

$$\mathbf{D}_{ij} = \frac{1}{3} \sum_{k=1}^N \bar{\mathbf{Q}}_{ij}^{(k)} (z_k^3 - z_{k-1}^3) \quad (6)$$

where \mathbf{A} , \mathbf{B} and \mathbf{D} are membrane, coupling and flexural rigidities, respectively, N is the total number of layers. Moreover, z_k is the distance of the middle surface between the k th layer as shown in Fig. 2. Furthermore, the coefficients of the transformed stiffness matrix of the k th layer $\bar{\mathbf{Q}}_{ij}^{(k)}$ are given by

$$\bar{\mathbf{Q}} = \mathbf{T}^{-1} \mathbf{Q} \mathbf{T}^{-T} \quad (7)$$

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