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Isogeometric buckling analysis of composite variable-stiffness panels

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ABSTRACT

Variable-stiffness panel with curvilinear fibers is a promising structural concept compared to constant-stiffness designs. However, for the traditional finite element analysis (FEA), there is no guarantee that the fiber angle is continuous and smooth due to element discretization. In this study, on the basis of Mindlin plate theory, the buckling behavior of composite variable-stiffness panels is investigated based on isogeometric analysis (IGA), whose main feature is that the continuity of fiber angle on the whole panel is guaranteed. In particular, since geometric stiffness matrix has a significant influence on the buckling behavior, it is obtained by performing a static analysis prior to the buckling analysis herein, which can further improve the prediction accuracy of current methods. Different fiber path functions, ply number, geometric parameter, as well as various boundary and loading conditions are adopted to verify the proposed buckling analysis method. Finally, the prediction accuracy, total degree-of-freedom and CPU time are compared with the traditional FEA, which indicates that the isogeometric buckling analysis method can provide an adequate accuracy in a more efficient manner.

1. Introduction

With the ever increased demand of lightweight design for aerospace industries, composite structures have been persistently popular for several decades. One of the primary advantages of utilizing composite panels into aerospace structures is the ability to tailoring mechanical property (e.g. stiffness and strength) by designing the laminate stacking sequence [1,2]. Compared to the constant-stiffness design, a superior structural performance can be achieved for variable-stiffness design, in which fiber path within the ply is curvilinear. Therefore, variable-stiffness design has spatially varying bending and coupling stiffness, indicating an enhanced design flexibility, which is beneficial in achieving the in-plane and out-of-plane stiffness requirements. Setoodeh et al. [3] demonstrated that a significant improvement of buckling loads can be gained by utilization of variable-stiffness panels. The improvement is attributed to the redistribution of in-plane loads to relatively stiff regions, and then resist buckling in critical regions. However, the rational formulation of variable-stiffness design problems is crucial, since the design efficiency would be significantly reduced with the increase of variables, more importantly, an inappropriate formulation may result in impractical structures with material discontinuities. In the previous works, three strategies were commonly used, i.e. patch design, blending design and curvilinear parameterization [4]. For instance, overlapping patches were used to guarantee the compatibility of fibers in adjacent regions [5]. Also, blending rules were proposed to serve as a continuity constraint in adjacent elements. Liu and Haftka [6] introduced a new measure of continuity by distinguishing the composition continuity and stacking sequence continuity, and then a composite wing was designed on the basis of this continuity constraint. By contrast, curvilinear functions were widely utilized to represent the fiber paths, where a pre-defined mathematical expression or its interpolation to prescribed key points are the essence. For example, linear variation fiber orientations were investigated by Gürdal et al. [7], and results show that the performance gain is significant compared to that of straight fiber. The linear variation fiber angle has been widely used in the analysis, design and manufacture of variable-stiffness composite panels [8–10]. In the works by Muc and Ulatowska [11], the contour lines of cubic functions were employed to describe the fiber paths. It was found that substantial improvement in the bending stiffness can be gained by spatially orienting fiber angles on their optimal directions. Four theoretical fiber path definitions were compared for conical shells by Blom et al. [12], and also trigonometric functions were employed to represent the fiber angles for conical shells. To enhance the design space, the fiber angles were then represented as cubic Bezier curves by Parnas et al. [13]. Similarly, nonlinear distribution of fiber angles was formulated by Lagrangian polynomials [14]. The fiber path was

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treated as a linear combination of pre-defined base fiber paths by Nagendra et al. [15]. Recently, Niu et al. [16] proposed a new parameterization method for fiber angle based on the potential flow theory, and results of tension test indicate that the strength of curvilinear laminate is improved significantly. To accelerate the design process of variable-stiffness panels, a reanalysis-based optimization method was proposed to substitute surrogate models, and the global optimization capacity is finally improved [17]. With the development of advanced manufacturing techniques for composite materials, Automated Fiber Placement (AFP) makes it possible to fabricate laminates consisting of layers with curvilinear fibers. As another similar concept, curvilinearly stiffened panels are also regarded as a type of promising configurations [18–20]. Curvilinear stiffeners have been demonstrated to be beneficial for cutout reinforcement of thin-walled panels to improve the strength margins by Hao et al. [21]. The advantageous loading path and tension field caused by curvilinear stiffeners were examined in detail by comparison of the ones of straight stiffeners [21]. Furthermore, Hao et al. [22] proposed a novel method to determine the division of near field and far field, and then performed the optimization of curvilinear stiffeners in the near field. Wang et al. [23] performed the buckling optimization of curved stiffeners based on a global/local coupled strategy, and a significant improvement of post-buckling performance was observed.

In the framework of traditional FEA, there is no guarantee that the fiber orientation angle is continuous and smooth due to element discretization for composite variable-stiffness panels, and the fibers are discretized at each element and dealt with as straight fibers, as shown in Fig. 1. To be specific, the fiber angle of ith element is defined as the tangential direction of path function using the coordinates of the center of the element, which means that each element has straight fibers with a constant fiber volume fraction rather than different orientation angle. Thus, fiber angle needs to be assigned for each element before FEA is performed, which would take a lots of CPU time. Moreover, this assumption would lead to a large prediction error of buckling behavior unless a very refined mesh size is adopted, which severely increases the computational burden of both geometry modeling and buckling analysis, especially for large-scale structures. In this case, IGA is a type of promising numerical computational method, which shows advantages over the traditional FEA. Therein, the Non-Uniform Rational B-Splines (NURBS) is employed not only as a geometry discretization technology, but also as a tool for analysis [24–27]. In this framework, geometric design and computational analysis can be integrated closely, thus the element refinement is simply implemented by re-indexing the parametric space without iteration with the geometry model, also without introducing geometric error. Moreover, the high-order continuity of IGA elements obtained by k-refinement are typically smooth beyond the traditional C^0-continuous finite elements. As a result, IGA is known as a robust numerical method that can be used to deal with composite structures, because of the superior characteristics of NURBS such as smoothness, high-order continuity and reduction of total degree-of-freedom (DOF) [25–28]. For variable-stiffness panels, IGA can provide significantly higher accuracy compared with the one by FEA though only a small number of DOF are required. However, little related work on variable-stiffness panels using the IGA can be found in the open literatures until now.

Buckling is the main failure mechanism for thin-walled composite panels [29–40]. In the traditional buckling analysis, geometric stiffness matrix is usually assumed to be uniformly distributed. For constant-stiffness designs, this assumption is adequate to simplify the buckling analysis. However, for variable-stiffness designs, the stress distribution is spatially varying, thus it is crucial to calculate the true geometric stiffness matrix before eigenvalue buckling equation is solved, which is usually neglected in the previous studies. In this study, Mindlin plate theory is utilized to carry out the buckling analysis, which is on the basis of first-order shear deformation theory. Except for this theory, Tounsi et al. [41,42] developed hyperbolic shear deformation theories without the need of shear correction factors, and the number of unknowns and governing equations is reduced to five or three, which have been successfully extended to the buckling analysis, bending analysis and free vibration analysis [43–55].

This paper is organized as follows. In Section 2, an overview of IGA is briefly presented, and then the framework for isogeometric buckling analysis with true geometric stiffness is introduced. In Section 3, variable-stiffness panels with linear variation fiber

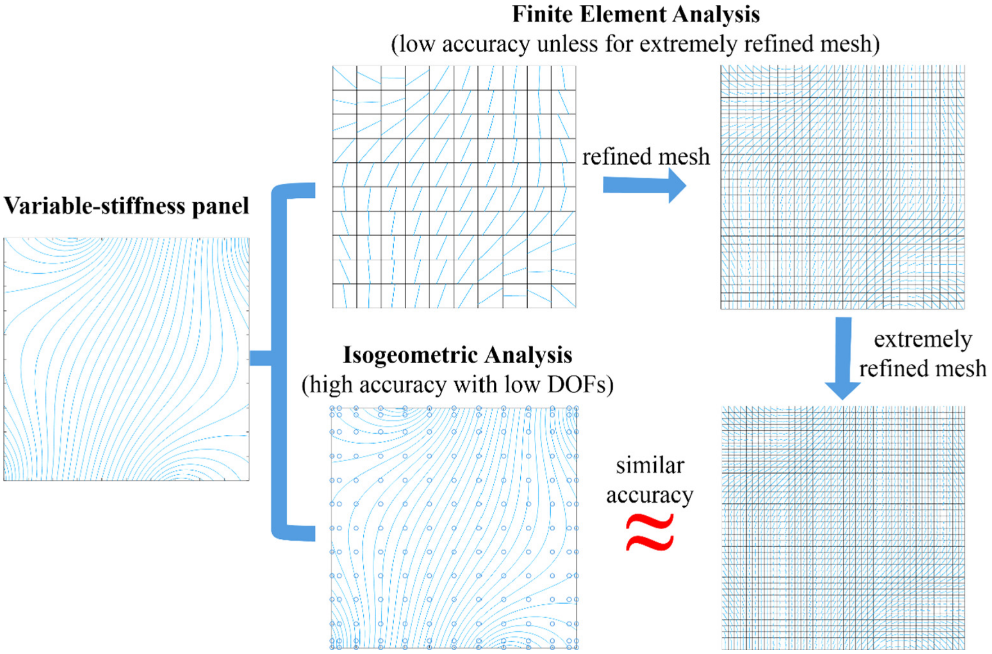

Fig. 1. Comparison of FEA and IGA for variable-stiffness panels.