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Abstract

A multi-layered shell formulation is developed based on a layerwise deformation theory [1] within the framework of isogeometric analysis (IGA). IGA utilizes Non-Uniform Rational B-splines (NURBS) to represent the geometry as well as to describe the field variables [2]. The high-order smoothness of NURBS offered the opportunity of capturing the structural deformation efficiently in a rotation-free manner. The derivation also follows a layerwise theory, which assumes a separate displacement field expansion within each layer, and considers transverse displacement component as C^0-continuous at layer interfaces, thus resulting in a layerwise continuous transverse strain states. Since the in-plane and through-thickness integrations are carried out individually, this approach is capable of capturing the complete three-dimensional stress states in a two-dimensional setting, which improves the computational efficiency. A knot insertion technique is utilized for the discretization in the through-thickness direction, and C^0-continuity is enforced by means of knot repetition at dissimilar material interfaces. The performance of the proposed model is demonstrated using multiple laminated composites and sandwich plates (including functionally graded material core) as examples. Numerical results prove the accuracy of the proposed formulation and show that the isogeometric layerwise shell is superior to its finite element counterpart.

Keywords: isogeometric analysis; layerwise; laminated composite; sandwich plate; functionally graded material.

1. Introduction

Laminated composites are increasingly used in industries such as civil engineering, automotive engineering, manufacturing and aerospace engineering. This rapid popularization in application is mainly owing to their characteristically high strength-to-weight ratio. Functionally graded material (FGM) as a special type of composite material is a mixture of two or more distinct materials (usually ceramic on top and metal at the bottom) with the volume fraction varying through one direction. It was first proposed by Bever and Duwez [3] and is well-known to provide high performance and multiple functions. Another appealing feature of FGM is that its material properties vary continuously in the thickness direction, in contrast to the traditional laminated composites where discontinuity exists at layer interfaces. However, the failure modes of laminated composites can be extremely complex, mainly because the majority of the dominated failure occurs in the inner layers of the composites and thus they are not easily detected a priori. Therefore, understanding how stresses and deformations distribute in the inner layers is of vital importance in determining why, how and under what loads structural failure will occur.

In order to understand and characterize the deformation and stress distribution, a number of theories have been developed for the analysis of multi-layered composite plates. The most propagated theoretical work for laminate composite structures is the classical laminate plate theory (CLPT) [4-5], in which it is assumed the state of stress is in-plane and in a layerwise fashion in addition to Kirchhoff's classical plate theory. This theory, however, is two-dimensional and therefore cannot predict the out-of-plane stress state. In three-dimensional domain, perhaps the most dominant theories in the field of composite laminates are

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