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Analysis of isotropic and composite laminated plates and shells using a differential quadrature hierarchical finite element method

Yang Wu, Yufeng Xing and Bo Liu

Institute of Solid Mechanics, Beihang University (BUAA), Beijing 100191, China.

Abstract: A *p*-version curved composite laminated shell element has been developed using the modified high order bases of a differential quadrature hierarchical finite element method (DQHFEM). The theoretical model of the shell is based on a layerwise theory with linear expansion in each layer. Exact geometry is established using the CAD technique of Non-Uniform Rational B-splines. As a result, the FEM discretization errors of geometry are eliminated. To solve the coupling difficulty of elements with different parameterization that commonly exists in complicated models, a novel method based on interpolation on arc length coordinates is proposed in this work. Even though the computational efficiency based on a layerwise theory is not as fast as those based on the equivalent single-layer theory, it produces as accurate results as the 3D theory and uses less DOFs as well as less input data than the 3D model. Additionally, because of the high convergence rate of the *p*-version FEM and the exact representation of the geometric model, the present elements are expected to produce more accurate results than the conventional *h*-version flat shell elements with the same number of DOFs. Numerical examples are provided to illustrate the accuracy as well as versatility of the present elements.

Keywords: layerwise theory; laminated shell elements; *p*-version finite element method; NURBS geometry; patch coupling.

1. Introduction

Composite laminates have been increasingly used in a variety of industrial areas, e.g., the aerospace, automobile and civil applications, due to their high stiffness and strength-to-weight ratios, long fatigue life, resistance to electrochemical corrosion [1, 2], etc. The wide applications of composite laminates have stimulated great interests in developing sufficiently accurate mathematical models to predict the mechanical behaviors of composite laminate structures. As the equations based on three-dimensional (3D) theories are found to be complicated and computationally expensive for laminated plates and shells, a lot of 2D theories have been developed considering the geometric features of plates and shells. These models are usually classified into two types: the equivalent single layer (ESL) models and the layerwise (LW) models [3].

The ESL model includes the classical laminated theory (CLT), the first-order shear deformation theory (FSDT) and the higher-order shear deformation theories (HSDTs). The CLT is computationally efficient. However, the neglect of transvers shear deformation may lead to inaccurate results for plates and shells that are not thin enough. The FSDT gives appropriate accuracy to the transvers deformation and is simple to implement. Therefore, this theory is widely used in developing finite elements for isotropic and composite laminated plates and shells with moderate thickness [4-6]. However, careful choice of the shear correction factor is demanded in FSDT, otherwise the accuracy of FSDT may be reduced. The HSDTs overcome this limitation since a non-linear shear stress distribution through the thickness is assumed. Even though the ESL models can usually predict results with reasonable accuracy. However, in some cases, particularly for sandwiches, the differences of the material properties of different layers makes it difficult for such theories to fully accommodate the bending behavior [7]. In such cases, the LW modes, introduced in the 1980s [8-10], are found to be more accurate in predicting the kinematics as well