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A mathematical model for calculating cross-sectional properties of modern wind turbine composite blades

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ABSTRACT

A wind turbine blade generally has complex structures including several layers of composite materials with shear webs. It is essential but also inherently difficult to accurately and rapidly calculate the cross-sectional properties of a complex composite blade for the structural dynamics and aeroelasticity analysis of the blade. In this paper, a novel mathematical model for calculating the cross-sectional properties of composite blades has been developed by incorporating classical lamination theory (CLT) with extended Bredt-Batho shear flow theory (EBSFT). The mathematical model considers the shear web effects and warping effects of composite blades thus greatly improves the accuracy of torsional stiffness calculation compared with the results from direct use of 3D laminate theories. It also avoids complicated post-processing of force-displacement data from computationally expensive 3D finite-element analysis (FEA) thus considerably improves the computational efficiency. A Matlab program was developed to verify the accuracy and efficiency of the mathematical model and a series of benchmark calculation tests were undertaken. The results show that good agreement is achieved comparing with the data from experiment and FEA, and improved accuracy of torsional stiffness calculation due to consideration of the shear web effects is observed comparing with an existing cross-sectional analysis code PreComp.

1. Introduction

Modern wind turbine blades generally are made of thin-walled shells with composite materials. Cross-sectional properties of the thin-walled shells, such as mass per unit length and sectional stiffness, of the composite blade are essential information for the structural dynamics and aeroelasticity analysis of the wind turbine blade, which is often represented as one-dimensional (1D) beam elements instead of three-dimensional (3D) shell elements [1]. However, due to the intrinsic nature of composite materials and the complexity of blade structural topologies, it is quite challenging to obtain the cross-sectional properties of a wind turbine blade.

Various methods have been proposed for calculating the cross-sectional properties of wind turbine blades, ranging from complicated finite-element techniques and 3D laminate theories to the simple two-dimensional (2D) lamination theory. The most sophisticated method to extract the cross-sectional properties of wind turbine blades is based on 3D finite-element techniques. 3D finite-element techniques, despite their ability for accurate stress and displacement analysis, cannot directly yield the cross-sectional properties of wind turbine blades. It relies on computationally complicated post-processing of force-displacement data [2]. One such post-processing tool is BPE (Blade Properties Extractor) [3], which is developed by Sandia National Laboratories and Global Energy Concepts. Currently, BPE is a module of NuMAD (Numerical Manufacturing And Design) [4], which is a windows based pre/post-processor to generate the 3D finite-element models of wind turbine blades. BPE applies a series of unit loads at the blade tip and transfers the displacement results of the 3D finite-element model of the blade to a series of MATLAB routines, which extract the stiffness matrices for the equivalent beam elements. In principle, BPE should be able to provide the most accurate cross-sectional properties because all 3D information can be captured by the 3D finite-element model. However, there are seemingly several challenges facing this method. Firstly, application of loads must be performed carefully to minimize the boundary layer effects. Additionally, the cross-sectional properties estimated by BPE are sensitive to the length of the blade segment, which one chooses to

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perform the finite-element analysis. Changing the length of the blade segment may even result in a singular stiffness matrix under some extreme situations [5].

Several other cross-sectional analysis tools based on 2D finite-element techniques have also been developed. Cesnik and Hodges [6] developed VABS (Variational Asymptotic Beam Sectional analysis) based on variational asymptotic method, which replaces a 3D structural model with a 2D model in terms of an asymptotic series of several small parameters of the structure. VABS requires a 2D finite-element discretization of the cross-section to generate its input files, which are the 2D mesh of the cross-section and the corresponding materials. For a practical wind turbine blade made of layers of composites, the generation of VABS input files is very tedious and requires a separate pre-processor called PreVABS [7]. Recently, Blasques [8] developed a cross-sectional analysis tool called BECAS based on anisotropic beam theory, which is originally presented by Gianotto et al. [9] for estimating the stiffness and the stresses of inhomogeneous anisotropic beams. Similar to VABS, BECAS also requires a 2D finite-element discretization of the cross-section. A separate pre-processor called Airfoil2BECAS [10], which is a python program, is needed to generate the input files for BECAS. Currently, the cross-section in Airfoil2BECAS is limited to 8 distinct regions, where layup and thickness information can be assigned.

Researchers have tried to obtain structural properties directly using 3D laminate theories. However, these theories cannot accurately estimate the torsional stiffness, which is overestimated by as much as 50–80 times using these theories [2]. The torsional stiffness is hard to evaluate because it is significantly affected by shear web effects and warping effects, which are difficult to model. This is particularly true for wind turbine blades, which commonly use asymmetrical cross-sections with several shear webs.

Compared to the finite-element techniques and 3D laminate theories, classical lamination theory (CLT) [11], which is an extension of the classical plate theory [12] to laminated plates, is fast and reasonably accurate. CLT can be used to combine properties and the angle of each ply in a pre-specified stacking sequence to calculate the overall effective performance for a laminate structure. Based on several reasonable assumptions, such as plane stress and linear strain, CLT transfers a complicated 3D elasticity problem to a solvable 2D problem [13]. Among the above assumptions, the assumption “each ply is under the condition of plane stress” is acceptable for composite blade due to the fact that wind turbine blades are thin-walled structures of composites.

CLT has been widely used for analyzing structural performance of composite materials [14,15]. In terms of composite blades, Bir [2,16] developed PreComp (Pre-processor for computing Composite blade properties) at National Renewable Energy Laboratory (NREL) based on CLT. PreComp does not need a separate pre-processor to generate the input files, which are the geometric shape and internal structural layout of the blade, and allows an arbitrary number of webs and a general layup of composite laminates. However, PreComp ignores the effects of shear webs in the calculation of the torsional stiffness. In other words, if the number of webs on a cross-section is changed, no change in torsional stiffness will be observed using PreComp. This is invalid for a practical blade cross-section, where the torsional stiffness will be enhanced as the number of shear webs increases.

For a closed thin-walled cross-section, Bredt-Batho shear flow theory (BSFT) [17] can be used to determine the torsional stiffness of the cross-section. BSFT is developed based on the assumption that the torsional stress is uniformly distributed across the thickness of the cross-section. Experiments show that this assumption is acceptable for most thin-walled cross-sections [18]. BSFT implicitly includes the dominant warping effects and it can provide reasonable results for the torsional stiffness of the closed thin-walled cross-section [18]. However, the original BSFT is developed for a single-cell cross-section. In order to apply BSFT to a practical wind turbine blade cross-section with shear webs, an extension of BSFT to cover multi-cells is required.

This paper attempts to incorporate CLT with an extended Bredt-Batho shear flow theory (EBSFT) [19] to develop a mathematical model, which extracts the cross-sectional properties of wind turbine blades in a fast and reliable way. Based on the mathematical model, a Matlab program is developed. In order to validate the developed program, a series of benchmark tests are performed for isotropic and composite blades as compared with ANSYS, PreComp and experimental data.

This paper is structured as follows. CLT and BSFT are summarized in Sections 2 and 3 respectively. EBSFT is discussed in Section 4. Section 5 details the development of a new mathematical model for cross-sectional analysis by incorporating CLT with EBSFT. Results and discussions are provided in Section 6, followed by a conclusion in Section 7.

2. Classical lamination theory (CLT)

CLT is an extension of the classical plate theory to laminated plates. The main assumptions of CLT are the Kirchhoff hypotheses [11]:

- Straight lines which are perpendicular to the mid-surface before deformation remain straight after deformation.
- The transverse normals are inextensible.
- The transverse normals rotate so that they are always perpendicular to the mid-surface.

The first two assumptions indicate that the transverse displacement is independent of the thickness coordination and the transverse normal strain is zero. The third assumption implies that transverse shear strains are zero. These assumptions are acceptable for thin laminates in most cases [11].

CLT has wide applications including stress and strain analysis of laminate plates. The validity of CLT has been established by comparing with experimental results and the exact solutions of the general elastic problems [20]. In terms of cross-sectional analysis, CLT can be used to calculate the effective engineering constants of angled plies.

The coordinate system used for an angled ply for the cross-sectional analysis using CLT is shown in Fig. 1.

The directions 1 and 2 constitute principal material coordinates while the directions x and y constitute global coordinates. The directions 1 and 2 are parallel and perpendicular to the fiber direction respectively.

The materials considered with CLT are orthotropic. The stress–strain relationship in principal material coordinates for an orthotropic material under plane stress condition can be expressed as:

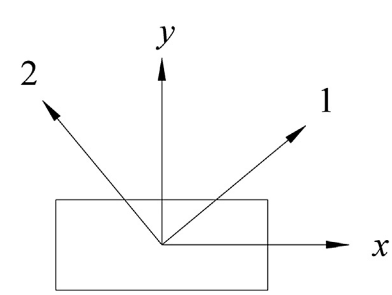

Fig. 1. Principal material and global coordinates.