



Effect of shallow-angled skins on the structural performance of the large-scale wind turbine blade



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ABSTRACT

Two shallow-angled symmetric and asymmetric skins, with off-axis fiber angles of less than 45°, were proposed and employed to a 5 MW wind turbine blade. For the symmetric configuration, shallow-angled skins were applied to both the pressure and suction sides of the blade, while, for the asymmetric configuration, only the pressure side was implemented with a shallow-angled skin, keeping the conventional 45-degree-angled skin for the suction side. The blade tip deflection, modal frequencies, buckling stability, and failure index were computed for off-axis fiber angles of 45°, 35°, and 25°. The use of shallow-angled skins improved blade bending stiffness and strength. The buckling resistance decreased for symmetric skins and remained unchanged for asymmetric skins; the former case was compensated for by increasing the core thickness. For both skin configurations, a reduction in the blade failure index of up to 18% and 38%, and mass reductions of up to 8% and 13% were demonstrated for the 35° and 25° shallow-angled skins, respectively.

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1. Introduction

Development of light-weight, large-scale blades with increased stiffness and strength is critical for the competitiveness of the wind turbine market. Large-scale wind turbines with longer blades to harness wind energy offer a cost-effective solution. These have the ability to capture power at low wind speeds; therefore, better land-wind resource utilization will be available in an effective and efficient manner, and the cost of energy (COE) can be lowered. The multi-MW wind turbine designs with rotor diameters ranging from 80 to 120 m have been investigated [1–3], and are expected to grow more in the future. A pre-design study of a 20 MW wind turbine with a rotor diameter of 252 m has been reported in Ref. [4].

Weight poses a challenge in the design of large-scale wind turbine blades. According to the square/cubic law, weight increases with cubic power, while the energy extracted from the wind increases only with the square power of the blade length. Over the years, researchers have successfully lowered the weight growth from an exponent of 3 to 2.3, using advanced composite materials and design improvements [5]. There are, however, still many potential weight-reduction opportunities associated with large-scale blade technology development. Blade weight reduction can be achieved using low-density materials such as carbon fiber [2,6,7],

and by improving manufacturing processes resulting in reduced fiber misalignment and waviness as well as a better fiber volume fraction [5].

Conventional design practices are limited to the use of bi-axial [± 45] and tri-axial [$0_2/\pm 45$] non-crimp fabric (NCF) laminates for the skins of a wind turbine blade, which constitute approximately 35–40% of the blade weight. However, considering the slender nature of a large-scale wind turbine blade, the conventional 45-degree off-axis fiber angle of the blade skins is not optimized. Lower cost/weight as well as higher stiffness and strength, can be achieved using the NCF skins with shallow off-axis fiber angles of less than 45°. As per the author's knowledge, no study has been conducted regarding the application of shallow-angled skins to a wind turbine blade.

The purpose of this study is to demonstrate that, in the real blade design, the shallow angles of the blade skins other than 45° needs to be explored together with optimizing the spar cap thickness in order to reduce the overall mass while meeting the design requirements. Two proposed shallow-angled symmetric and asymmetric skin configurations are applied to a utility-scale 5 MW wind turbine blade. The blade tip deflection, failure index, buckling stability and modal frequencies are then evaluated for both skin configurations at off-axis fiber angles of 45°, 35°, and 25°. The increased bending stiffness and strength of the blade with shallow-angled skins are lowered to match that of the blade with the conventional 45-degree-angled skins by removing the spar cap mass.

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This paper begins with the property evaluation of a simple, tri-axial, NCF skin laminate at various off-axis fiber angles, ranging from the conventional 45° to the shallow angles of 35° and 25° . The proposed shallow-angled skin configurations are then implemented to a 5 MW wind turbine blade, whose geometry and layup is downscaled from a 100 m Sandia All-glass 13.2 MW wind turbine blade [8]. Finally, the conclusions are presented following the results and discussion Section.

2. Shallow-angled skin laminates

2.1. Composite layup of a wind turbine blade

A blade is a hollow structure made of two shells glued together, with shear webs fitted between them (Fig. 1). The typical composite layup of a blade consists of the unidirectional (UD), bi-axial (BX), and tri-axial (TX) laminates and a foam core material [8]. The UD laminates primarily endure the bending loads and are used for the spar cap and trailing edge reinforcement regions. The TX skins surrounding the core are used to maintain the aerodynamic shape and to withstand buckling loads. The BX skins and foam core construction at the shear webs are used to transfer shear loads between the pressure side (PS) and suction side (SS) shells. It should be noted that current design practices in most cases are limited to the use of BX and TX skin laminates with off-axis fiber angles set to the conventional 45° , allowing variation only in the thickness.

2.2. Tri-axial laminate with shallow fiber angles

The stiffness and strength of conventional 45-degree-angled skin in the longitudinal direction are not optimized. Fig. 2a shows a TX NCF skin laminate $[0_2/\pm\theta]_s$, where θ is the off-axis fiber angle in degrees. The laminate consisted of E-glass/Epoxy plies with material properties listed in Table 4. Using classical laminate theory (CLT), the computed in-plane effective stiffness and strength of the laminate at various off-axis fiber angles are shown in Fig. 2b–c. For a shallow fiber angle of 25° , the effective longitudinal stiffness (E_L) increased by 26.6%, and the effective tensile strength (X_{Ef}) increased by 104.5%, as compared to the values at 45° . The shear strength (S_{Ef}) decreased by only 24.5%. Fig. 2d shows the estimated Tsai-Wu failure index (TWFI) at various stress ratios (R : 0.2–0.4) decreases for shallow fiber angles of 35° and 25° . The stress ratio, R , is defined as the ratio of the in-plane shear stress to the in-plane normal stress.

The results suggest that for loading situations where the in-plane normal stress is significantly higher than the in-plane shear stress (in the case of a wind turbine blade), the use of the shallow-angled laminate is more effective than the conventional 45-degree-angled laminate.

3. Development of a 5 MW wind turbine blade model

3.1. Down-scaled 5 MW wind turbine blade

To evaluate the concept of shallow angled skins, a 5 MW wind turbine blade was selected. National Renewable Energy Laboratory (NREL), USA established the specifications of a utility-scale 5 MW 03-bladed wind turbine for offshore sites, however, the blade layup information is not reported [9]. Consequently, the selected 5 MW wind turbine blade model of length 61.5 m was then established by down-scaling the geometry and layup of the 13.2 MW wind turbine blade of length 100 m, designated as SNL-100-00, developed by Sandia National Laboratories, USA [8]. The material properties of UD, BX and TX laminates, GelCoat coating, resin and foam being used are listed in Table 2. The detailed information regarding layups, geometry (chord, pitch-axis and twist angle and web locations), mass and stiffness properties is well documented in Ref. [8].

Figs. 3 and 4 show the geometry and layup distributions of the down-scaled blade. The GelCoat and extra resin are not shown for brevity. The specification comparison of the down-scaled blade with Sandia and NREL blade models is listed in Table 1. It should also be noted that the SNL 100-00 blade had three shear webs. The purpose of the third web was to increase the buckling resistance at the aft-panel region. The down-scaled blade had only 2 webs and its SS aft-panel buckling resistance was increased via thickening the foam core by approximately 14%.

3.1.1. Estimation of ply stiffness properties

To investigate the structure performance of the blade with shallow angled skins, a ply-level finite element model was developed. The UD ply properties were back-calculated from Sandia provided laminate stiffness properties [8], using CLT. Various mixing ratios of UD ply that provided the equivalent BX and TX NCF laminate stiffness properties are listed in Table 3. The back-calculated UD ply longitudinal, transverse and shear stiffness properties, denoted by E_x , E_y and E_{xy} , respectively, are listed in Table 4. The UD ply ultimate longitudinal tensile and compressive, transverse tensile and compressive, and shear strengths properties,

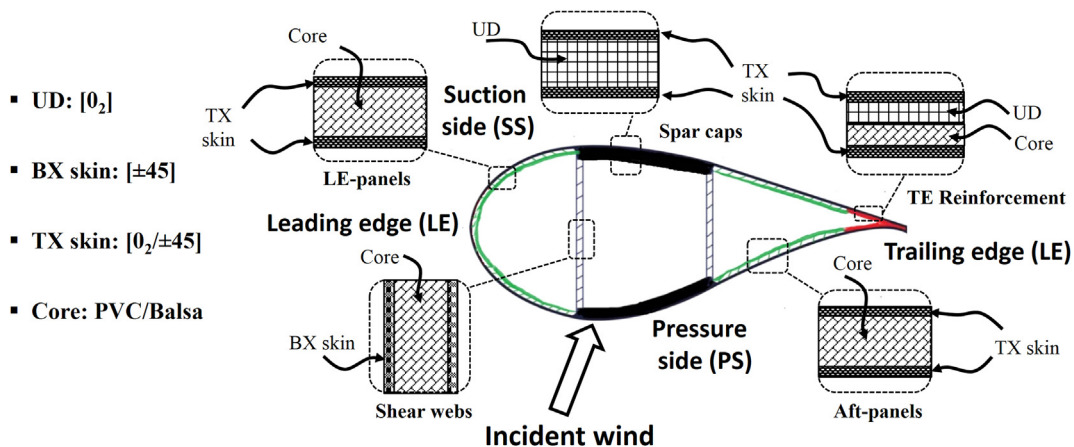


Fig. 1. Typical composite layup of a blade [8].

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