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Development of a physics-based multi-scale progressive damage model for assessing the durability of wind turbine blades

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ABSTRACT

A physics-based multi-scale progressive damage model was developed for predicting the durability of wind turbine blade structures. Computational micromechanics was coupled within a continuum damage mechanics (CDM) framework, and implemented through a user-defined subroutine within commercial finite element software, for evaluating sub-critical damage evolution and stiffness degradation of the blade structure. The study is the first step in developing an accurate prediction model for composite wind turbines that accounts for the multi-scale nature of damage in rotor blades. The quasi-static and fatigue simulation results demonstrate the ability of the model to predict the evolution of damage in the critical regions of the blade structure, which is an important contribution and essential for increasing the accuracy of damage tolerance analyses and for certification of composite structures. A parametric study of blade geometric parameters also revealed a correlation with damage evolution, providing valuable insight for optimization of blade designs.

1. Introduction

As the global need for renewable energy expands, designing wind turbines with greater power harnessing capacity is paramount. One solution is to increase the rotating blade length, however, this raises the demands on the blade structure since its weight, and thus gravitational load, also increases. Therefore, minimization of blade weight becomes an even more important design requirement. When in service, composite wind turbine blades must resist damage caused by extreme wind gusts as well as cyclic external loading [1]. As the blades rotate during operation, changing aerodynamic and gravitational loads give rise to cyclic bending in the flap-wise and edge-wise directions (see Fig. 1a), which causes damage to evolve and the stiffness to degrade. Since wind turbines are expected to last 20–30 years in service, the fatigue requirements for blade designs are quite high. Despite composite materials having excellent fatigue properties, progression of damage during service is one of the main limiting factors for increasing rotor blade length. Since the evolution of fatigue damage in composite materials currently used for rotor blades is not well understood, large safety factors are employed which lead to highly conservative designs. With a better understanding of the damage evolution characteristics of rotor blade structures, it will be possible to decrease these safety factors and optimize designs by tailoring the laminate stacking sequences and through parametric studies, thereby reducing service life costs. Thus, there is a need to develop comprehensive modeling tools for predicting progressive failure of composite wind turbine blades (i.e., damage tolerance analysis) if larger wind turbine structures are to be improved and certified. Specifically, we need to develop multi-scale models that consider the different length scales at which different damage modes are observed to nucleate and progress [2].

Only a few studies have investigated damage and failure modes of full-scale wind turbine blades [3–6]. In the report by Sorensen et al. [3], examination of fully collapsed rotor blades revealed that the main damage modes were spar cap-skin and upper–lower skin joint adhesive debonding, sandwich panel face-core debonding, laminate delamination, and blade local buckling (see Fig. 1a). They also indicate that laminate delamination was present in the regions containing many ply cracks. Other studies observed that ply delamination was the main damage mode that initiated structural collapse of the blades [4,6]. These studies all focus on the structural collapse of rotor blades and the associated damage modes at the macroscopic scale, whereas microscopic damage modes are not discussed at great length. The studies by Lambert et al. [7] and Sorensen [1] reveal that a high density of matrix

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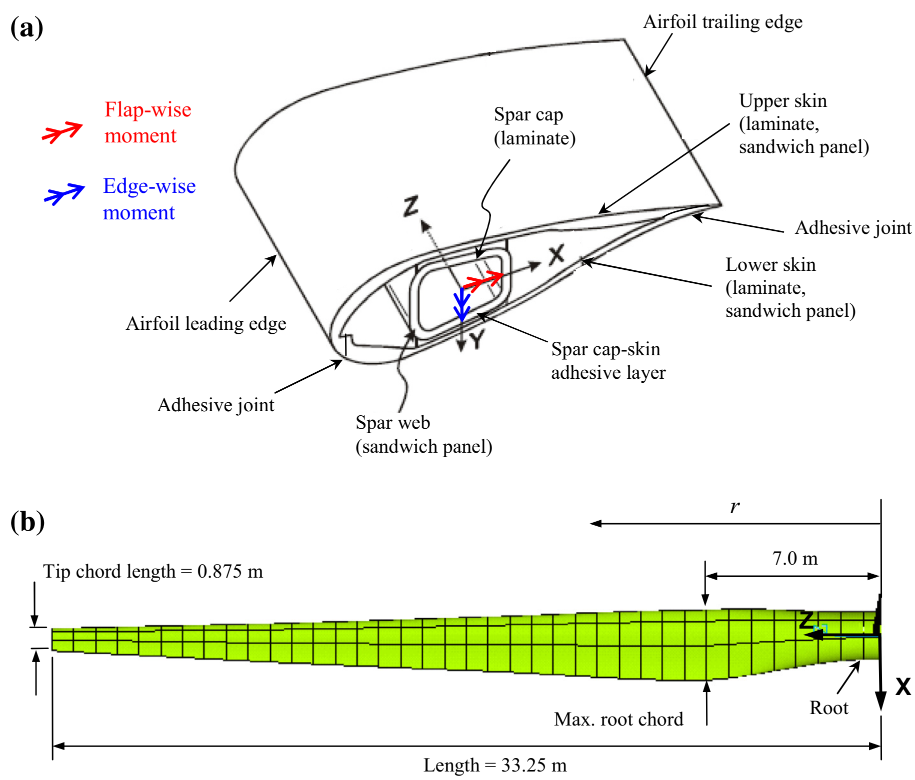

Fig. 1. (a) Schematic of typical two-spar wind turbine blade with structural details and (b) geometry of two-spar blade analyzed in this study.

cracks is a precursor to more critical damage modes such as delamination, but there is no comprehensive effort to quantify the effects of these microscopic cracks. It is clear that microscopic laminate ply cracks will accumulate and lead to the onset of critical damage modes, which will initiate structural failure modes such as adhesive joint debonding and local buckling.

A number of recent studies have reported computational models that analyze catastrophic failure in wind turbine blades subjected to quasi-static or cyclic loads [4,8–18]. Certain models do not explicitly consider damage evolution in wind turbine blades [9,15], while others only consider damage evolution in the materials used to manufacture wind turbine structures [13,16,18]. In addition, although some models simulate damage evolution in rotor blades, they often utilize failure criteria such as Hashin's or Puck's criteria without accounting for any physical damage modes or the corresponding material stiffness degradation [10,12,14], which must be considered in order to accurately capture the nonlinear behavior of the materials used in the analysis of these structures and for service life prediction. Failure criteria lack any physical basis and do not properly consider the ply constraining effects in laminates, which was clearly illustrated in a recent article by Talreja [19]. For studies that consider fatigue damage evolution, simple damage models based on stress-life (S-N) test data or nonphysical macroscopic variables are often used [10,11,17], providing limited confidence in these approaches. In general, most models reported in the literature rely on extensive test data for damage model calibration, which requires complicated and costly experimental programs every time there are structural design changes. This is regarded by the authors as a major drawback since the predictive capabilities of existing approaches are limited in scope and application. Furthermore, the reported wind turbine rotor blade progressive failure models predominately account only for the macroscopic damage modes and the ensuing structural collapse [4,8], without considering the progressive nature of sub-critical microscopic intra-laminar damage, which is imperative for predicting onset of macroscopic failure modes. Thus, consideration of the multi-scale nature of progressive damage in wind turbine blades is vital for accurate long-term durability assessment.

Based on the above considerations, the multi-scale nature of damage evolution in composite structures has attracted significant attention in recent years, leading to the development of useful multi-scale approaches whereby the evolution of sub-critical damage modes has been accounted for [20–28]. For instance, Bogdanor et al. [20] developed a new probabilistic multi-scale model that accounted for the stochastic nature of failure in composite laminates. In this model, the variability of the constituent material properties at the microscopic length scale is linked to the laminate length scale using a reduced-order computational homogenization model, and predictions for the tensile strength variability of open hole multidirectional laminated plates has been reported. Ply-level failure data from unidirectional laminate experiments were used to calibrate the computational model, however, in-situ ply strengths were not considered in the study. Camanho and co-workers [24], on the other hand, have developed a model that considers the evolution of intra-ply damage (i.e., ply cracking) as well as delamination growth for multidirectional laminates. Micromechanics within a continuum framework was used to address the energetics of ply cracking, where damage evolution laws for both tensile and compressive loading follow mathematical functions that utilized experimentally-derived fracture toughness values. In addition, a bilinear cohesive damage model was used to account for delamination and was implemented into a finite element (FE) model using cohesive elements. The intra-ply damage model was also implemented into a commercial FE package and foreign impact damage progression in flat composite plates was simulated. Following a continuum damage mechanics based approach, Waas and co-workers [26] have developed a multi-scale model for multidirectional laminates in which the microscopic damage evolution