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Assessing progressive failure in long wind turbine blades under quasi-static and cyclic loads

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ABSTRACT

Predicting progressive failure and consequential loss in the load-bearing capability of large-scale composite wind blades is vital for accurately assessing their service life and maintenance. A physics-based multi-scale damage model describing progressive ply cracking and joint adhesive debonding in blades under both quasi-static and cyclic loading is presented. The complete structure of the blade was considered including the shell-spar adhesive joint and shell-root adhesive joint. For quasi-static loading, the geometrical transition region of the blade was observed as the critical ply crack damage region, which was in agreement with previous experimental results. The matrix micro-cracking damage was mainly caused by high gale wind speeds, and adhesive debonding ultimately initiated at the shell-spar joint. The blade tip deflection increased nonlinearly with increasing wind speeds, reaching 29.0% of the blade length at 19 m/s. For cyclic loading, sub-critical damage grew along the length of the blade with increasing cycles, gradually increasing the normal and shear stresses in the joint adhesive layer as the crack density increased, eventually leading to local shell-spar adhesive debonding. The simulation methodology presented here will be useful for assessing the durability and increasing the safety and accuracy of service life prediction of large-scale blade structures.

1. Introduction

Wind power is a clean, relatively inexpensive and renewable energy source, which has been growing dramatically over the past few decades [1,2]. In order to capture wind energy more effectively, there exists a demand to increase the scale of wind turbines in commercial wind power generation [3]. However, as wind turbines increase in size, so do the requirements for material and structure designs of rotor blades due to the increase of blade weight and the associated gravitational load. To meet this challenge, fiber-reinforced laminated composites are widely used in large rotor blades due to their high stiffness-to-weight ratio, strength-to-weight ratio, and resistance to fatigue failure [4,5]. However, during a typical 20-year service life, multiple evolving damage modes resulting from extreme combined cyclic loads (i.e., gravitational force, centrifugal force, and aerodynamic force) can occur in rotor blades [6–8]. These damage modes typically initiate as undetectable sub-critical cracks and progress into critical damage modes that ultimately leads to catastrophic failure. It is therefore vital to predict their evolution concurrently under both quasi-static and fatigue conditions as well the consequent loss in load bearing capability of the structure in order to facilitate an improved design for rotor blades.

Typical damage modes observed in large wind turbine blades include matrix micro-cracking, cohesive joint debonding, and inter-ply delamination, which have been studied in previous reports [9–11]. Generally, matrix micro-cracking is the first to initiate in composite laminates under both quasi-static and cyclic loading conditions. This ply cracking typically does not cause the final failure but causes appreciable stiffness degradation; and to address this, a number of excellent models have been developed to evaluate stiffness loss caused by matrix micro-cracking in composite laminates. These popular methods include elasticity approach [12], continuum damage approach [13], ply discount method [14], synergistic damage mechanics approach [15,16], and damage

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accumulation approach [17]. From the inspection of damage in composite blades, it has been revealed that matrix micro-cracking is likely caused by critical cyclic loading [11,18]. In regards to model development focused on wind turbine composites, a physically-based failure model was developed to investigate the mechanism of matrix micro-cracking in composite blades under cyclic loading [19], however, the blades were simplified as beam structures. A physics-based multi-scale progressive damage model was also developed to assess the matrix cracking evolution of the blades under quasi-static and cyclic loading, in which full-scale geometries of rotor blades were considered [20].

With regards to adhesive joint debonding, full-scale composite blade tests revealed that debonding was the main cause of rotor blade structural collapse [21,22]. The initiation of debonding was reported to be caused by voids in the adhesive layer due to the reduction of joint strength [23]. A finite element study showed that the debonding initiated and propagated progressively in the edge of the adhesive bond line according to the high shear stress in adhesive layers [24]. In addition, fatigue loads were found to have an import influence on the debonding evolution of the composite blade root joint [25]. In addition, the ensuing delamination can lead to the buckling of laminated composite materials even if at a lower level of compressive load [26,27], and the delamination and buckling coupled phenomenon of large composite blades was regarded to govern the ultimate collapse of large composite blade [21,28]. In a failure test, the delamination of a spar cap was likely responsible for the catastrophic failure of a rotor blade at the transition region due to local compressive forces [10].

The final failure of wind turbine blades is observed to involve a combination of damage modes [10,19]. In composite laminates, ply cracks can induce inter-laminar delamination cracking, which is one of the main sources of failure [29]. A high density of ply cracks is also reported to lead to localized delamination and skin/spar cap adhesive debonding in turbine blades [30]. A study of the interaction of these damage modes is vital to accurately capture the nonlinear behavior of composite wind blades under both quasi-static and fatigue loading. However, the previous studies on this topic have only modeled one damage mode of rotor blades [19,20,25,26], which limits their applicability for practical wind turbine design and durability assessment. Furthermore, the geometric models of these studies mainly represented only one component of rotor blades such as the root, and not the full structure including the root, spar and shell; clearly, an important limitation of reported results in optimizing rotor blade designs for better life-time performance. Therefore, a full-structural model considering sub-critical and critical damage modes is required to assess the durability and increase the accuracy of service life prediction of large scale blade structures.

The aim of this study is to assess the progressive damage of large composite rotor blade, considering the co-effects of matrix micro-cracking damage and joint adhesive debonding under both quasi-static and cyclic loads. Herein, the full structure of a composite blade was modeled and the details of the shell-root and shell-spar adhesive joints were included. The constitutive equations for the damaged laminates, based on a synergistic damage mechanics [15,16,20,31], were implemented as a user-defined material subroutine (UMAT) in the commercial finite element code ANSYS for the assessment of matrix micro-cracking damage. A cohesive zone model (CZM) [32–34] using contact elements was employed to predict the initiation and growth of debonding. Based on Weibull distribution of wind speeds [6], the effects of potential wind speed pressures on the progressive damage of the blade were evaluated by quasi-static and fatigue simulations. Results presented included the initiation and propagation of both matrix micro-cracking damage and adhesive debonding, moreover, the interaction of the damage and debonding was also discussed by cyclic loading cases.

2. Damage mechanics model

2.1. The progressive damage model

In order to evaluate the effect of matrix micro-cracking of rotor blades, an approach based on micromechanics and continuum damage mechanics to predict the crack density and stiffness degradation of the blades has been reported in our previous work [20]. In this approach, the stress tensor, σ_{ij}, was characterized by the strain tensor, ε_{kl}, as [15,35]:

$$\sigma_{ij} = C_{ijkl}\left(D_{ij}^{(\alpha)}(\rho)\right)\varepsilon_{kl} \tag{1}$$

where ρ represents the crack density for cracks in a given ply orientation, the defined as damage mode α. A second-order damage tensor is used to represent the damage, as [13,36]:

$$D_{ij}^{(\alpha)}(\rho) = \frac{\kappa_\alpha t_\alpha^2}{s_\alpha t} n_i n_j \tag{2}$$

where κ_α is the constraint parameter, t_α is the cracked-ply thickness, s_α is the average crack spacing, t is the total laminate thickness, and n_i ($i = 1, 2, 3$) are the crack surface normal unit vector components. For any general symmetric laminate under in-plane multiaxial loading, the stiffness tensor for a given crack density ρ is defined as:

$$C_{ijkl} = C_{ijkl}^{0} - \sum_{\alpha=1}^{N} C_{ijkl}^{\alpha} = \begin{pmatrix} \dfrac{E_x^0}{1-\nu_{xy}^0\nu_{yx}^0} & \dfrac{\nu_{xy}^0 E_y^0}{1-\nu_{xy}^0\nu_{yx}^0} & 0 \\ & \dfrac{E_y^0}{1-\nu_{xy}^0\nu_{yx}^0} & 0 \\ \text{Symm} & & G_{xy}^0 \end{pmatrix} - \sum_{\alpha} a_\alpha D_\alpha \begin{pmatrix} 2a_1^{(\alpha)} & a_4^{(\alpha)} & 0 \\ & 2a_2^{(\alpha)} & 0 \\ \text{Symm} & & 2a_3^{(\alpha)} \end{pmatrix} \tag{3}$$

where C_{ijkl}^{0} and C_{ijkl}^{α} are, respectively, the undamaged stiffness tensor of the laminate and stiffness changes caused by damage modes α. The terms $a_i^{(\alpha)}$ and D_α are, respectively, the orthotropic damage constants and effective damage parameters for all damage modes present during loading of the laminate. The constraint parameters, κ_α, and damage constants, $a_i^{(\alpha)}$, for any general symmetric laminate were computed using the micro damage mechanics procedure that utilizes finite element computations of average crack surface displacements in representative volume elements for each damage mode, as discussed in Ref. [16].

To simulate the structural degradation of the blades, an energy-based approach was employed to predict ply crack density ρ for a general multidirectional laminate under multi-axial loading, as reported in our previous work [15]. Considering both crack opening (Mode I) and crack sliding (Mode II), new cracks are assumed to form when:

$$\left(\frac{w_I}{G_{Ic}}\right) + \left(\frac{w_{II}}{G_{IIc}}\right)^2 \geq 1 \tag{4}$$

where w_I and w_{II} represent the work required to close the new

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