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Modeling matrix cracking in composite rotor blades within VABS framework ☆

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ABSTRACT

This paper deals with modeling of the first damage mode (i.e. matrix micro-cracking) in helicopter rotor or wind turbine blades and how this effects the overall cross-sectional stiffness. The helicopter rotor or wind turbine rotor system operates in a highly dynamic and unsteady environment leading to severe vibratory loads present in the system. Repeated exposure to this loading condition can induce damage in the composite rotor blades. These helicopter rotor or wind turbine blades are generally made of fiber-reinforced laminated composites and exhibit various competing modes of damage such as matrix micro-cracking, delamination, and fiber breakage. There is a need to study the behavior of the composite rotor system under various key damage modes in composite materials for developing Structural Health Monitoring (SHM) system. Each blade is modeled as a beam based on geometrically non-linear 3-D elasticity theory. Each blade thus splits into 2-D analyzes of cross-sections and non-linear 1-D analyzes along the beam reference lines. Two different tools are used here for complete 3-D analysis: VABS for 2-D cross-sectional analysis and GEBT for 1-D beam analysis. The physically-based failure models for matrix in compression and tension loading are used in the present work. We detect the matrix cracking using two failure criterion: Matrix Failure in Compression and Matrix Failure in Tension which are based on the recovered field. We set the strain variable which drives the damage variable for matrix cracking and this damage variable is used to estimate the reduced cross-sectional stiffness. The procedure presented in this paper is implemented in VABS as matrix micro-cracking modeling module. To investigate the matrix failure model, three examples are presented which illustrate the effect of matrix cracking on cross-sectional stiffness by varying the applied cyclic load. Finally, the stiffness degradation of composite cross-section of rotor blade due to matrix micro-cracking is correlated to the life of composite rotor blade using damage accumulation model. At the end, an empirical equation is given for the Stress Intensity Factor (SIF) to simulate the matrix micro-crack growth in future.

1. Introduction

Damage mechanics of composites deals with quantitative descriptions of the physical events (such as initiation, propagation, and fracture) that alter composite material(s) when it is subjected to mechanical loads and aging (long-term performance of composites). Its main aim is to develop an efficient framework that describes the composite material response caused by the evolving damage state(s). Most of the work on damage mechanics uses state variables (may be measurable, for example, micro-crack density) to represent the effects of damage on the stiffness and remaining life of composite material that is damaging due to mechanical loads.

During the recent years, many researches focus on the damage and failure analyzes of fiber-reinforced composites due to the increase of demand for composite structures (such as composite rotor blades) in industries. Matrix cracking (occurs either in compression or in tension), delamination/debonding, fiber breakage (occurs either in compression or in tension) are the typical damage modes in composite rotor blades. These mechanisms that lead to failure of composite materials are not fully understood yet, even after the World-Wide Failure Exercise (WWFE) [1,2]. WWFE concluded that most of the criteria were unable to capture some of the trends in the failure envelopes of the experimental results and most of the expressions proposed to predict each failure mode are still to some extent empirical. These physical damage modes should establish suitably when failure takes place in composite structures, and also describe the post-failure behavior of composite structures for better performance. The need for predicting failure

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in composites has led to the proposal of several failure criteria in the literature. These are usually either stress-based or strain-based failure criteria. There is no unique system of classification so far for failure criteria in composites. The failure criteria are classified broadly based on the approach followed in their derivations: non-physically-based (non-phenomenological, *not* associated with the failure modes) and physically-based (phenomenological, associated with the failure modes). Paris [3] described the above classification in a NASA report, evaluated existing composite failure criteria and explored the possibilities for modification of material and failure models to account for large deformations, progressive failure, and interaction of damage accumulation.

Generally, damage in composite materials initiates with the matrix micro-cracking damage mode. Matrix micro-cracking occurs in both monotonic loading and fatigue loading and leads to more serious damage such as delamination or fiber fracture, with final failure usually involving a combination of damage modes. The number of micro-cracks increases monotonically with load or with the number of load cycles until a saturation density is reached. Due to the interlaminar cracks, separation of the plies takes place locally. These separations of plies are called interior delaminations as against the exterior delaminations associated with free edges in laminates. The stiffness reduction due to matrix cracking in composite materials has been modeled by various approaches such as the shear-lag model [4], variational approach [5], self-consistent scheme [6], continuum damage approach [7,8], elasticity approach [9], internal variable method [10], and ply discount method [11,12]. The earliest approach used the ply discount method where transverse matrix cracks were modeled by completely neglecting the transverse stiffness of cracked plies. However, cracked plies can take some loading which means that this method, underestimates the stiffness of cracked laminates. In addition, gradual changes in stiffness with increasing crack densities, which is needed for tracking health of the laminate, cannot be modeled by the ply discount method. The final failure mode is fiber breakage which is associated with the ultimate failure of the ply.

Most of the research in the area of damage modeling in rotor blades is done by assuming isotropic material properties. In this case, the damage modeling uses an equal percentage reduction in the bending and torsion stiffnesses. Some studies have considered crack models based on a fracture mechanics approach but these have also been limited to isotropic materials [13]. The first step towards damage modeling in composite rotor blades was taken by Lakshmanan and Pines [14] who modeled damage in the flexbeam of a bearingless rotor blade which extends across entire width of the flexbeam of bearingless rotor blade. Nuismer and Tan [15] developed the first damage model, i.e., matrix cracking model for cross-ply laminates using a plane strain assumption for $[\pm\theta_m/90_n]$ family of composites. An approximate elasticity solution is presented for the stress–strain relations of a cracked composite lamina in the form of two-dimensional compliances and shown that the cracked lamina compliances depend upon the overall laminate construction in which the lamina is contained. Pinho et al. [16] developed a 3-D failure criteria for laminated fiber-reinforced composites based on a physical model for each failure mode considering non-linear matrix shear behavior. They have shown that the developed criteria accurately predicted failure envelopes and trends. Pinho et al. [17] implemented the developed model using explicit finite elements and observed the inclination of the fracture plane in matrix compression, the $\pm 45^\circ$ failure pattern of a $(\pm 45^\circ)_{ns}$ tension specimen.

Puck and Schurmann [18,19] proposed a matrix compressive failure model based on the Mohr–Coulomb criterion and further developments were later carried out by Davila et al. [20,21] for LaRC02/03 failure criteria. Davila et al. computed the stresses in the updated misalignment frame to check the matrix failure using LaRC02/03 matrix failure criterion. Pinho [22] implemented these failure criteria into a Finite Element (FE) code and proposed a modification for the consideration of frictional stresses. Finally, this modification leads to more conservative failure load predictions.

Mao and Mahadevan [23] developed a mathematical model for fatigue damage evolution in composites and studied the characteristics of damage growth in homogeneous materials. Continuum damage mechanics concepts are used in their model to evaluate the degradation of composites under cyclic loading condition. This model is more accurate than the other mathematical models of fatigue, both in modeling the rapid damage growth early in life of composite rotor blades and near the end of fatigue life. Pawar [24] studied the Structural Health Monitoring (SHM) system of the composite rotor blades by addressing two important issues: (1) structural modeling and aeroelastic analysis of the damaged rotor blade and (2) development of a model based rotor health monitoring system. Pawar and Ganguli [25] studied the effects of 3-key damage modes (matrix cracking, delamination/debonding, fiber breakage) using a thin walled composite beam analysis for helicopter rotor blade applications. They modeled matrix cracking at laminate level, delamination/debonding and fiber breakage at the lamina level by adjusting the A, B and D matrices for composite laminates. They found that the bending and torsion stiffness loss due to matrix cracking is about 6–12% and 25–30%, respectively, and due to delamination/debonding is about 6–8% and 40–45%, respectively and maximum bending stiffness loss observed in the final damage mode, fiber breakage. Pawar and Ganguli [26] developed a health-monitoring and life-estimation strategy for composite rotor blades. In their work, the reduced cross-sectional stiffness obtained by physics-based models is expressed as a function of the life of the structure using a phenomenological damage model. They observed that the life consumption in the matrix-cracking zone is about 12–15% and the life consumption in delamination/debonding zone is about 45–55% of the total life of the blade.

Mandell et al. [27] presented an analysis of trends in fatigue results on the fatigue of composite materials for wind turbine blades. They analyzed trends in static and fatigue performance for a range of materials, geometries and loading conditions and prepared SNL/MSU/DOE Fatigue of Composite Materials Database which is updated annually. These detailed tests allow evaluation of various blade materials options in the context of more realistic representations of blade structures.

Brown [28] studied the effect of thermal-cycling-induced micro-cracking in fiber-reinforced polymer matrix composites and observed the effect of micro-cracking on the dimensional stability of composite materials. He focused on micro-crack density which is a function of the number of thermal cycles and concerned about the changes in laminate coefficient of thermal expansion (CTE) and laminate stiffness. He considered four different Thornel fiber types (T50, P55, P75 and P120) and three matrix types (Fiberite's 934 epoxy, Amoco's ERL1962 toughened epoxy and YLA's RS3 cyanate ester). He also selected different fiber CTE's which range from $-0.50 \times 10^{-6}/^\circ F$ to $-0.80 \times 10^{-6}/^\circ F$. He also considered three lamination sequences: cross-ply configuration, $[0/90]_{2s}$, and two quasi-isotropic configurations, $[0/+45/-45/90]_s$ and $[0/+45/90/-45]_s$. The layer thickness of the selected materials ranges from a nominal 0.001 in. to 0.005 in. He also considered three different thermal cycling temperature ranges: $\pm 250\,^\circ F$, $\pm 150\,^\circ F$ and $\pm 50\,^\circ F$. Finally, he presented some experimental comparisons by examining the effect of layer thickness, fiber type, matrix type and thermal cycling temperature range on micro-cracking and its influence finally on the laminates.

Hodges and Yu [29] presented an approach for the modeling of composite beam structures which are commonly used in wind turbine blades and helicopter rotor blades. This modeling