Composite Structures 131 (2015) 905–916

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Probabilistic micromechanical analysis of composite material stiffness properties for a wind turbine blade

Ghulam Mustafa *, Afzal Suleman, Curran Crawford

University of Victoria, Department of Mechanical Engineering, P.O. Box 3055, Victoria, BC V8W 3P6, Canada

ARTICLE INFO

Article history:
Available online 4 July 2015

Keywords:
Micromechanics
Unit cell
Reliability
Composite
Fiber
Monte Carlo

ABSTRACT

This work presents a coupled approach for stiffness property prediction of composite materials used in wind turbine blades using an advanced micromechanics and reliability-based methodologies. This approach demonstrates how to map the uncertainties in the fiber and matrix properties onto the equivalent stiffness properties of composite laminates. Square and hexagonal unit cells were employed for the estimation of the composite equivalent properties. The finite element formulation of the unit cells were performed in the ANSYS Multiphysics. The results from numerical experimentation conform well with the available test data and to the results from the Modified Rule of Mixture (MROM). A probabilistic analysis using Monte Carlo Simulation with Latin Hypercube Sampling was used to assess the uncertainties in the equivalent properties according to the variability in the basic properties of the constituents. Furthermore, a sensitivity analysis based on the Spearman Rank Order correlation coefficients was carried out to highlight the influence of important properties of the constituents. As an illustration, the above approach is applied to analyze a 5 MW wind turbine blade section under static loading. Results demonstrate the possibility of the coupled approach at macro level (structure) from micro level (unit cell) with the aim to design robust structures.

1. Introductions

The size of wind turbines is increasing to capture more energy and this trend will continue into the future [1]. Several multi-MW prototype wind turbines exist for offshore applications [2,3]. The power of a wind turbine scales as square of the rotor diameter, while the mass of the blade (for similar conceptual designs) scales as the cube of rotor diameter. Considering these scaling laws one might predict that in the end material costs would govern and avert further scaling. The cost of the blade would then also scale as the cube of rotor diameter but advanced structural concepts reduce its scaling exponent to $\sim$2.5 [4]. A polymer-based composite material is a good choice for large structures such as wind turbine blades. The high strength-to-density ratio, high stiffness-to-density ratio, good fracture toughness, fatigue performance and suitability for use in fast production of large structures makes composites a good choice for their use in structural applications. The composite properties provided by the manufacturer are generally the average properties in a particular manufacturing environment. On top of this, manufacturers usually don't mention the number of tests that they performed to obtain the average. This adds risk to structural design, especially for large-scale composite layups such a blades. It is impossible to completely control variation in the composite properties. There are many factors that contribute to that variation including: batch-to-batch production, manufacturing conditions like temperature, pressure, and humidity, curing time, labor skill, along with the property variations in the basic building blocks of the ply (the fiber and the matrix). These variations in the mechanical properties of composite materials are due primarily to variation in the properties of the constituents - the fiber and matrix [5]. This variation in properties establishes a scatter in the response of a structure made up from this material, for example, the deflection of the wind turbine blade. Therefore, it is necessary to consider the variable nature of composite properties at the design stage. Current wind turbine blade design is based on a deterministic approach with a large factor of safety to ensure target static and fatigue limits [6]. It is very expensive experimentally to obtain the design allowables for a composite laminate in a deterministic approach as significant test campaigns for each candidate layup are required.

The micromechanics (MM) based homogenization approach is good alternative to characterize the stiffness properties of

* Corresponding author.
E-mail addresses: gmustafa@uvic.ca (G. Mustafa), suleman@uvic.ca (A. Suleman), curranc@uvic.ca (C. Crawford).

http://dx.doi.org/10.1016/j.compstruct.2015.06.070
0263-8223/

composite materials [7,8]. The Rule of Mixtures (ROM), also known as the Simple Rule of Mixture (SROM), is one of the oldest and simplest forms of micromechanics for calculating mechanical properties of unidirectional plies [7,9,10]. Halphin [11] proposed a Modified Rule of Mixture (MROM) as there are shortcomings in calculating the transverse Young's modulus and in-plane shear modulus using SROM. Dong and Feng [12] simulate the behavior of various unit cells using an asymptotic homogenization technique. Other researchers have considered the uncertainty in the basic constituent's properties with the homogenization approach. Kamiński and Kleiber [13] calculated the first two probabilistic moments of the elasticity tensor using the homogenization method of composite structure. However, due to the complicated mathematical formulation, these studies are of limited applicability.

The present study aims at bringing together high fidelity micro-model based stiffness calculations of composite materials and probabilistic analysis. The homogenization approach coupled with a Monte Carlo Simulation method is used to predict variability in composite material properties. The paper is organized as follows. Section 2 introduces the concept of the Representative Unit Cell (RUC) models and the stiffness properties calculation procedure using Rule of Mixture and homogenization based approaches. Section 3 provides details of the Monte Carlo Simulation along with Latin Hypercube Sampling and sensitivity analysis. Section 4 presents the results. Section 5 details the applicability of the method to a wind turbine blade section analysis. Section 6 summarizes the most important conclusions drawn from this study and highlights the topics require investigation in the future.

2. Theory

2.1. Representative Unit Cell (RUC) models

The wind turbine blade structure is made up of polymer-based composite laminates, which are in turn made up of plies stacked in a certain sequence. These plies are made up of fiber and matrix constituents. All these levels are divided into two main groups, the macro and micro levels as shown in the Fig. 1. Customarily, one moves right or left in these levels via localization and homogenization. A homogenization procedure provides the response of a structure given the properties of the structure's constituents. Conversely, the localization method provides the response of the constituents given the response of the structure.

The fibers are randomly arranged in the real unidirectional (UD) ply. The far left side of Fig. 2 shows a cross section of a continuous UD ply [14]. There is no obvious regular pattern in which the fibers are arranged. A true representation of the fiber arrangement is shown in the middle of Fig. 2. To aid computation, an idealized fiber arrangement is used, as shown in the far right side of the Fig. 2. In this study, two idealized RUC models are used: square (SQR) RUC and hexagonal (HEX) RUC, as shown at the bottom of Fig. 2. Other choices for the RUC, such as triangular RUC, could be exploring in the future.

2.2. Rule of Mixture (ROM)

Structures made up from composite materials can be designed by tailoring the constituent properties. This requires high fidelity analysis and design of composite materials. Micromechanics is an approach that handles this scenario by establishing a relationship between the constituents and the ply or lamina. Several theoretical models have been proposed for the prediction of composite properties from those of the constituent fiber and matrix. An investigation of the existing micromechanics models has been summarized by Hashin [15]. The Rule of Mixtures (ROM) is one of the oldest and simplest forms of micromechanics for calculating the mechanical properties of unidirectional plies [7,9–10]. There is not an accurate prediction for the transverse Young's modulus E_{22} and in-plane shear modulus G_{12} through SROM. This deficiency is overcome by the Modified Rule of Mixture (MROM) as proposed by Halphin [11].

2.3. Ply stiffness computational procedure with RUC

It is not easy to determine experimentally the longitudinal and transverse shear moduli of unidirectional composites. It is also difficult to predict these moduli using MROM as they require ply level information [7]. Thus, numerical techniques such as the finite element method (FEM) are needed to facilitate these predictions. The stiffness properties of a unidirectional (UD) ply are calculated using FEM from the constituent's properties: the fiber and resin (or matrix) properties; fiber volume fraction V_f which controls the geometric parameter of the RUC. For example, in the case of SQR RUC, the radius of the unit cell is given as $r_f^{SQR} = \sqrt{V_f xy/\pi}$, where x and y is lengths of square unit cell as shown in Fig. 2.

The behavior (stress and strain fields) of fiber and resin under uniform loading is quite different due to their different material properties. Therefore, special attention must be paid in order to

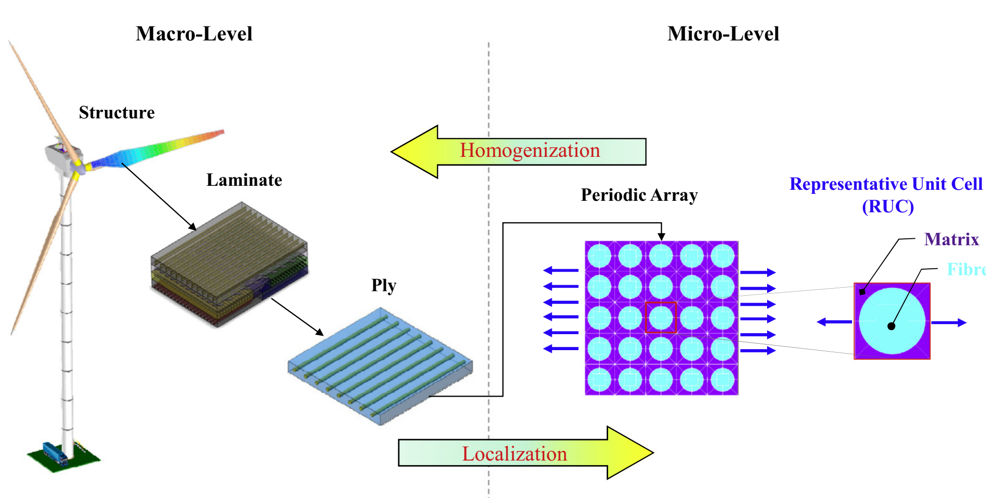

Fig. 1. Macro and micro levels.