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Carbon nanotube reinforced hybrid composites: Computational modeling of environmental fatigue and usability for wind blades

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ABSTRACT

The potential of advanced carbon/glass hybrid reinforced composites with secondary carbon nanotube reinforcement for wind energy applications is investigated here with the use of computational experiments. Fatigue behavior of hybrid as well as glass and carbon fiber reinforced composites with and without secondary CNT reinforcement is simulated using multiscale 3D unit cells. The materials behavior under both mechanical cyclic loading and combined mechanical and environmental loading (with phase properties degraded due to the moisture effects) is studied. The multiscale unit cells are generated automatically using the Python based code. 3D computational studies of environment and fatigue analyses of multiscale composites with secondary nano-scale reinforcement in different material phases and different CNTs arrangements are carried out systematically in this paper. It was demonstrated that composites with the secondary CNT reinforcements (especially, aligned tubes) present superior fatigue performances than those without reinforcements, also under combined environmental and cyclic mechanical loading. This effect is stronger for carbon composites, than for hybrid and glass composites.

1. Introduction

The future perspectives of wind energy utilization depend on the development and reliability of extra-large off-shore wind turbines [1]. Wind turbines are subject to long term cyclic mechanical and environmental loading, involving complex off-axis tensile, compressive and shear loading. The creation of such wind turbines requires the development of new, strong, fatigue resistant materials, which can sustain cyclic, random mechanical, thermal and environmental loadings over years keeping their high stiffness and integrity.

A number of experimental and computational studies have been carried out to develop better materials for wind turbines [1–7]. Among various ideas to enhance the performances of the composite materials for wind energy applications, two approaches attract a growing interest of research community and industry: hybrid composites and nanoreinforced composites.

Hybrid composites (e.g., mixed carbon and glass fibers) allow to combine the advantages of both groups of fibers (for the case of carbon/glass composites, low price of glass fibers, low weight and high tensile strength and stiffness of carbon fibers) and compensate their weaknesses (again, high costs and low compressive strength of carbon fibers) [4–17]. So, Ong and Tsai [4] demonstrated that the full replacement of cheap and easily available glass fibers by very stiff, strong and lightweight carbon fibers for an 8 m wind turbine blades leads to 80% weight savings, and cost increase by 150%, while a partial (30%) replacement would lead to only 90% cost increase and 50% weight reduction. In a number of works, the strength and damage mechanisms of hybrid composites were studied It was reported, among others, that the incorporation of glass fibers in carbon fiber reinforced composites allows the improvement of their impact properties and tensile strain to failure of the composite. Manders and Bader [11] observed an enhancement of the failure strain of the carbon fiber reinforced phase when "carbon fiber is combined with less-stiff higher-elongation glass fiber in a hybrid composite".

Another approach to improve the composite performances (additionally to and keeping in place the advantages of both strong fibers and polymer matrix) is nanoreinforcing the matrix. It has been observed in many studies that the addition of small amount of nanoparticles (e.g. graphene, carbon nanotubes, or silicates and clay particles with high aspect ratios) to fiber reinforced composites can be used to improve composite properties [18–29]. According to Ref. [18], matrix-dominated properties (flexural and interlaminar

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shear strength) are drastically improved by the CNT additions to fiber-reinforced thermoplastic composites, while fiber-controlled properties (such as tensile strength and stiffness) are improved only slightly. In Refs. [19–21], the authors compared the composites with CNTs dispersed in matrix and distributed in fiber sizing. They observed that the crack initiation toughness increases (by 10% if CNTs in sizing and by 25% if in matrix) and the crack propagation toughness decreases (by 30–50%) when CNTs are placed in sizing [20]. However, in the system with carbon fibers, both crack initiation and propagation energies were improved by CNT addition in matrix [21], what is related with CNT bridging and other toughening mechanisms (crack deflection, blocking). In Ref. [22], it was shown that the tensile strength of glass fibers increases significantly with increasing CNT content. 45% increase in shear strength is achieved by adding 0.015 wt% nanotubes into glass fiber reinforced vinyl ester composite [23]. 30% enhancement of the interlaminar shear strength was achieved by deposition of multi and single walled CNT on woven carbon fabric fibers in epoxy matrix [26,27]. Interlaminar toughness and strength of alumina fiber reinforced plastic laminates were improved by 76% and 9% due to the radially aligned CNTs in both inter-laminar and intra-laminar regions [28]. Thus, the secondary nanoreinforcement (e.g., carbon nanotubes or nanoclay distributed in polymer matrix or fiber sizing) have positive effect on the shear and compressive strength, fracture toughness and fatigue resistance of composites.

However, the question arises whether and to which degree this potential of material improvement is useful and usable for wind turbine blades, i.e. structures to be used under conditions of combined mechanical and environmental loading, high humidity, off-axis, complex loadings. A series of computational studies is carried out here in order to clarify the potential of these material modifications for wind blade materials. Using the numerical experiments, we seek to investigate how and whether the effects of hybrid and nanoreinforced structures of polymer composites (both each of them and combined) are beneficial for the fatigue resistance and service properties of the composites to be used in the wind turbine conditions. To do this, we use the computational micromechanics approach, based on multiscale and multi-element unit cell models [8,29], developed and tested in Ref. [29]. Collecting the literature data on the local materials properties and humidity effect on the properties of different phases, we introduce these data into the 3D multiscale computational models of composites and evaluate and compare the output materials performances. Carrying out computational experiments (numerical testing) of various composite structures, we explore the structure–mechanical properties relationships and can develop recommendations toward the improvement of the materials properties.

2. Computational model: generation, simulation, material properties

2.1. 3D hierarchical computational model: Python based model generation

Due to the large difference of the dimension scale of the fiber reinforced composite (macro-scale) and CNTs reinforcement (nanoscale), we use here the concept of macro-micro multiple-step modeling [29], to simulate the damage evolution in the material.

In order to carry our systematic computational studies of the microstructure–strength relationships of hybrid composites with secondary CNT reinforcements, a number of 3D computational models reflecting the hybrid composite structures should be generated. For this, a special Python based software code for the automatic generation of unit cells with multiple cylinder-like reinforcements [29–34] was generalized and improved. The newly developed code allows to generate hierarchical FE models with predefined structures, including the macro-scale unit cell (with hybrid unidirectional/misaligned fibers and variable fiber content) and lower scale unit cell model (with aligned/random oriented carbon nanotubes, surrounded by the effective interface layers, see Refs. [37,38]), automatically. Examples of the models are shown in Fig. 1a. For comparison, we show a micrograph of a carbon fiber with CNTs, reprinted from Ref. [39] (Fig. 1b).

2.2. Micro-scale unit cell generation with multiple high aspect ratio CNTs: algorithm of cylinder distribution

For the generation of lower scale unit cell models with many high aspect ratio carbon nanotubes, the following approach has been used. The carbon nanotubes were presented as cylinders. The reinforcing CNTs are randomly distributed in the fiber–matrix interface and (in some models) randomly oriented. To take into account the interface effect, the generalized effective interface layer concept was used [30–38].

In order to distribute the high aspect ratio CNT cylinders in the microscope unit cell, the following algorithm was used. The condition that the CNTs do not overlap is written as follows:

$$\begin{aligned} &d_{f-f} \geq 2R_f \\ &d_{CNT-CNT} \geq 2r_{CNT} \\ &d_{f-CNT} \geq R_f + r_{CNT} \end{aligned} \tag{1}$$

where, d_{f-f}, $d_{CNT-CNT}$, d_{f-CNT} are distances between closest fibers, closest CNTs and a fiber and CNT, respectively, R_f – radius of fiber, r_{CNT} – radius of carbon nanotube. When generating the unit cell with multiple randomly oriented CNTs, the program places each new CNT into the cell one after another, using random number generator to get the new CNT location and checking that the reinforcements don't overlap. For this, the distance between straight lines (CNT cylinder axes) located in different planes was calculated using the spatial vector projection theory. We take $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ as two points on the central line of new CNT cylinder (the line is marked as L_1) and $P_3(x_3, y_3, z_3)$ and $P_4(x_4, y_4, z_4)$ as two points on the central line of one of the existing CNT cylinders (marked as L_2). From the analytic geometry, the direction vector of l_1 and l_2 are described as

$$\begin{aligned} \overrightarrow{L_1} &= (x_2 - x_1, y_2 - y_1, z_2 - z_1) \\ \overrightarrow{L_2} &= (x_4 - x_3, y_4 - y_3, z_4 - z_3) \end{aligned} \tag{2}$$

The vector of common perpendicular (marked as l) of the two lines is given by:

$$\begin{aligned} &\vec{L} = \overrightarrow{L_1} \times \overrightarrow{L_2} \\ &= \begin{vmatrix} i & j & k \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_4 - x_3 & y_4 - y_3 & z_4 - z_3 \end{vmatrix} \end{aligned} \tag{3}$$

After some simplifications

$$\begin{aligned} &\vec{L} = \overrightarrow{L_1} \times \overrightarrow{L_2} \\ &= \begin{pmatrix} (y_2 - y_1)\cdot(z_4 - z_3) - (y_4 - y_3)\cdot(z_2 - z_1), \\ (z_2 - z_1)\cdot(x_4 - x_3) - (z_4 - z_3)\cdot(x_2 - x_1), \\ (x_2 - x_1)\cdot(y_4 - y_3) - (x_4 - x_3)\cdot(y_2 - y_1) \end{pmatrix} \\ &= (E, F, G) \end{aligned} \tag{4}$$

Taking arbitrary points (P_1 and P_3 as examples) on L_1 and L_2, we consider the projection of line P_1P_3 on the common perpendicular, which in fact represents the distance between the two lines.

The direction vector of line P_1P_3 can be described as