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Simulation of tensile behavior of plant fibers using the Discrete Element Method (DEM)

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ABSTRACT

Tensile behaviors of plant fibers significantly affect mechanical performance of the fiber reinforced composites. A numerical model was developed to simulate the tensile behavior of a plant fiber using the Discrete Element Method (DEM). The model fiber was constructed with spherical particles bonded together. The model outputs were tensile strength (σ_{macro}) and Young's modulus (E_{macro}) of fiber. Tensile tests were conducted to measure these two properties of hemp fiber to calibrate model micro-parameters. Simulation results showed that the most influential micro-parameters were micro-strength of the bond (σ_{micro}) and Young's modulus of particles (E_{micro}). The following relationships were found: σ_{micro} = 1.89 σ_{macro} and E_{micro} = 0.99 E_{macro}. Using the tensile test data of hemp fiber, the calibrated values were 721.81 MPa for σ_{micro} and 19.50 GPa for E_{micro}. With the results from this study, the micro-parameters can be determined for DE modeling of any plant fibers, such as flax and Jute.

1. Introduction

Natural fibers have gained popularity to be used in bioproducts such as natural fiber reinforced composites because of the concerns for the environment and depleting fossil fuels which arise from using synthetic fibers. Besides being biodegradable, natural fibers also have other attractive properties, such as high mechanical strength relative to the low density. Among approximately 2000 species of natural fiber plants, a few of them provides around 90% of the natural fibers in the world [1]. Hemp is one of them. Natural fibers extracted from plant stalk are in bundle forms. A fiber bundle consists of individual single fibers connected by middle lamella (Fig. 1), providing the mechanical strength to the fiber. There is a small channel inside a single fiber called lumen. The channel, which is filled with proteins and pectin, contributes little to the strength of natural fibers.

When tensile loads are applied to natural fiber based products such as continuous fiber reinforced composites, particularly along the fiber direction, a primary concern is rapture of fiber boundles in the matrix. This failure of fiber bundles significantly decreases the mechanical performance of the bioproducts. Therefore, information on tensile strengths of fiber bundles is critical for making high strength bioproducts. Tensile properties of natural fibers including tensile strength and Young's modulus have been documented using experimental studies. Tensile strength of hemp fibers varied from 244 to 900 MPa [3–5], which were close to those of flax fiber (345 to 950 MPa) [6]. The values reported for Young's modulus of hemp fiber ranged from 8.6 to 35 GPa [3–5]. The variability in tensile properties is attributable to many factors, including growing condition and agronomic practices. For example, the specific tensile strength of hemp fibers increased from 22.9 to 44.0 cN/tex when plant density increased from 50 to 350 plants/m^2 [7]. Retting condition is expected to have some effects. However, similar tensile strengths have been reported for retted hemp (343 MPa) and unretted hemp (358 MPa) [4]. Another affecting factor is related to the cross section area of natural fibers. When the cross section area of hemp fibers was envisioned as circular the reported tensile strength and Young's modulus were respectively 277 MPa and 9.5 GPa while when it was considered as rectangular they were 244 MPa and 8.6 GPa [5].

Traditional experimental methods to analyze tensile behaviors of natural fibers are time consuming and requires special equipment (such as Instron and universal machines) that may not always available. Thus, researchers have taken modeling approach to simulate tensile behaviors of natural fibers. The Discrete Element Modeling (DEM) introduced by Cundall [8] can simulate dynamic behaviors of continues and discontinues solid materials [9]. This method can also be used to simulate tensile behaviors of material. For example, Khattak and Khattab [10] developed a 2D DEM model to analyze tensile behavior of synthetic fiber reinforcement composites. Roux et al. [11] used a DEM model to simulate the rapture response of muscle tendon complex. In simulating tensile tests of high-carbon steel using the DEM, Chen et al. [12] found a correlation between DEM input parameters and mechanical

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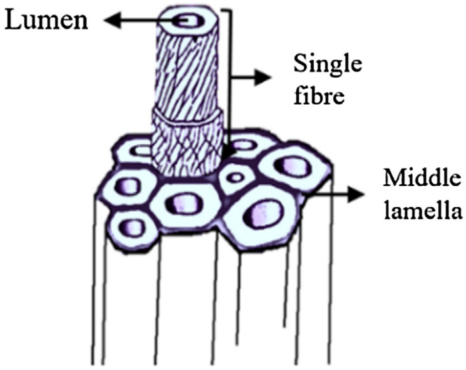

Fig. 1. A fiber bundle. Source [2]: permission from National Programme on Technology Enhanced Learning with modification. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

parameters of the steel. These studies have demonstrated that the DEM was a promising tool to simulate varieties of materials under tensile loads. However, there has been only one DEM model developed to predict the tensile behavior of hemp fibers [4]. In this existing model, the total number of particles used to construct a fiber was 15 only. This few numbers of particles are insufficient to reflect the structural failure of a hemp fiber bundle under a tensile load. Furthermore, calibrations of DEM input parameters of natural fibers have not been thoroughly investigated.

Calibration of model parameters is one of the major challenges of using the DEM. The main difficulties are that many parameters are required as model inputs, model parameters (referred as to micro-parameters) are not measurable, and they are not directly related to properties of the material (referred to macro-parameters) that is simulated. The most common method that has been used is the reverse calibration procedure in which micro-parameters are adjusted until the macro-parameters match experimental results [13]. Using this method for calibrations, rests are required. If the relationships between micro-parameters and macro-parameter are developed, one can use the relationship for predictions without the need of doing tests.

Therefore, the main objectives of this study were to (1) measure tensile properties of hemp fiber, (2) develop a model using the DEM to simulate a plant fiber under tensile loads, (3) estimate the combination effects of micro-parameters on macro-properties, and (4) establish relationships between the DEM input micro-parameters and output macro-properties, which was essential for future simulations of micro-dynamics of plant fiber using the DEM models.

2. Tensile experiment

2.1. Fiber bundle description

In this investigation, hemp (*Cannabis sativa*) fiber, which is the most popular types of plant fibers, was used for tensile tests. It was obtained from a previous study conducted by Hermann [14]. The hemp was grown in Parkland Region of Western Manitoba, Canada. The plant population density was 100 plants/m^2. Plants, randomly chosen in the field, were harvested by hand at the beginning of September when 95% of the mature seed present was hard. Hemp stems, 200-mm long, were cut in the middle of the plants, and 650–850 mm from the soil surface. To obtain fibers from those stems, water retting was used by placing the stems in a container for 7 to 10 days in water at 36 °C and 6.8 pH. Then stems were rinsed in tap water and placed in drying racks, next to heater fans, for four days. After that, fiber bundles were detached from the dried stems using a reciprocating blade-type breaker/decorticator. The final fibers are shown in Fig. 2.

Fig. 2. Hemp fiber samples used for tensile tests.

2.2. Fiber bundle dimension measurements

To determine the tensile strength of a fiber, the cross-section area of the fiber is required. Thus, dimensions of the cross-sections of fiber were measured. A total of 30 fibers were randomly picked up from the fibers shown in Fig. 2. Through an optical microscope (Wild Heerbrugg AG model, Gais, Switzerland) (Fig. 3), it was observed that the cross-section of the fiber was close to a rectangular. For measurement, a fiber was glued on two aluminum cube blocks covered by a double-coated carbon conductive tape (Ted Pella, Inc.). The fiber was placed under the microscope, which was connected to a computer to measure the width and thickness. For each dimension, nine readings were taken along approximately a 10-mm of the middle section of the fiber, and the average width or thickness of the nine readings was reported.

2.3. Tensile experiment

A 5 kN Instron (Ametek Instruments, LS model, USA) was used for the experiment on tensile properties of fibers. The Instron comprised of a frame, a drive system, a controller, a load cell, and two grips to hold specimen. The Instron was controlled via EXYGEN*Plus* software, which allowed the user to define input parameters and record the data.

To prepare for tensile tests, the fiber sample was attached to a clipboard frame using permanent fabric adhesive (Fig. 4a). This was to prevent the fiber sample from slipping off the clamps of the Instron during pulling. The “window” of the clipboard gave an effective fiber

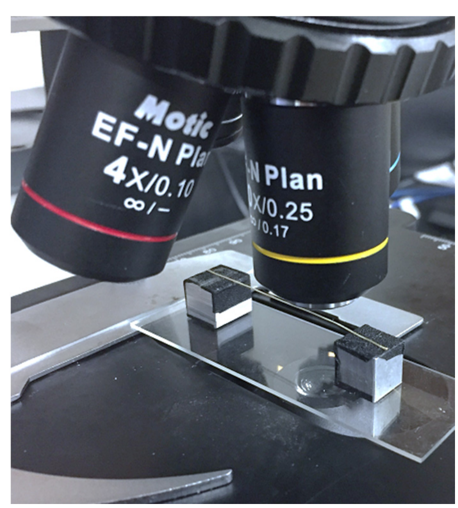

Fig. 3. Setup for measuring the thickness and width of a fiber using an optical microscope. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)