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Switchgrass ultimate stresses at typical biomass conditions available for processing

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Abstract

Biomass tensile and shear ultimate failure stresses were measured with the aim of identifying biomass "weakest mode of failure" or "natural fracture point" as a basis for future grinder designs. Switchgrass (*Panicum virgatum* L.) ultimate stresses were determined for Alamo and Kanlow varieties over ranges in maturity and moisture content. Alamo had greater ultimate tensile stress than Kanlow ($P = 0.0091$), with mean values of 97.8 and 89.7 MPa, respectively. Alamo had greater ultimate shear stress than Kanlow ($P = 0.0091$), with mean values of 20.5 and 17.9 MPa, respectively. Shear was the "weakest mode of failure". Grinders that use knives, shear bars, and mechanical pinch points that apply opposed-sliding actions are expected to be more energy efficient. Mean ultimate tensile stress and shear stress were significantly different between switchgrass varieties. A survey of failure stresses for a range of biomass feedstocks is recommended for future study. Ultimate tensile stress increased two-fold as elapsed time after harvest increased from 2 to 386 h, with a corresponding (confounded) decrease in moisture content of ~60–10% (wet basis (w.b.)). Future study should isolate whether the effect was due primarily to moisture or aging. Tensile-dominant size reduction should be conducted early in the harvest process and at a high moisture content to minimize energy consumption for grinding. Ultimate shear stress was relatively insensitive to switchgrass maturity, elapsed time after harvest, and moisture content.

Keywords: Grinding; Moisture content; *Panicum virgatum* L.; Shear stress; Size reduction; Tensile stress

1. Introduction

Biomass is a renewable feedstock for conversion to products and/or industrial and domestic energy [1]. Biomass size reduction can be an important step in processing raw biomass and in densifying and handling an otherwise unwieldy crop [2,3]. Mechanical grinding that applies failure stresses to biomass materials is a common process, though several biomass materials have limited availability of published physical properties for engineering optimization of grinding [4]. For example, switchgrass (*Panicum virgatum* L.) is a promising herbaceous energy crop in the US [5,6], though few properties applicable to size reduction are known. Data for other crops may not apply because tensile and shear strengths vary widely among forages [7].

Previous studies measured physical properties such as ultimate tensile and shear stresses to design high-capacity forage choppers [7], improve rice harvest mechanization [8], and to design no-till planter coulters to slice wheat straw residues [9]. Recent emphasis on profitable bioenergy with minimal investment of grinding energy raised interest in ultimate tensile and shear stresses of wheat straw [4].

Ultimate tensile stress tests have unique problems in gripping and holding biomass without crushing sample ends, as experienced with wheat straw [10,11], rice straw [8], and corn stalk [12]. Special grips for biomass tensile tests included pipe components with sandpaper and soft rubber for rice straw [8] and a clamp frame with self-locking jaws, rubber tape, glue, and triple thicknesses of stalk material for wheat [4]. Caution was noted as elastomeric-type grips could confound measurements for biological materials due to visco-elastic responses of both materials to loads [11]. Ultimate shear stress measurement has fewer problems than tensile stress measurement,

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though a variety of shear devices were used. Double shear box [11,13], double shearing device [8,12], and modified soil shear apparatus with load cell [9] were reported.

Accuracy in calculating failure stress depends on accurate measurements of complex cross-sections being loaded to failure [12]. Wheat stalk cross-section was assumed as an elliptic ring measured by microscope [4,10]. Other measurement instruments included micrometer [9,13], or a drill bit pinning method [8]. Non-uniform cross-sectional shapes complicate area determinations and often require simplifying assumptions such as circular shape [9].

Various internode test positions selected for tensile and shear tests [10–13], and different test moisture contents of wheat [7,9–11,13], rice straw [8], ryegrass [14], and sorghum stalk [15] are additional factors in comparing results of biomass strength tests.

Measurements of ultimate tensile and shear stresses of energy crops, such as switchgrass, are needed to provide a database to design and develop optimized size reduction equipment for minimum grinding energy input. Measurements should be conducted for a range of biomass conditions available for processing such as maturity level and moisture content. Objectives of the study herein were as follows:

(1) Determine ultimate tensile and shear stresses of selected cross-sections of switchgrass stems.
(2) Evaluate the effects of switchgrass variety, moisture content, and maturity on ultimate tensile and shear stresses.

2. Methods and materials

2.1. Test sample collection

Alamo and Kanlow varieties of switchgrass (*Panicum virgatum* L.) were selected for the study because they have high biomass yield, broad adaptability to various growing conditions, and a long period of availability [16]. Switchgrass stem samples were manually harvested beginning the first week of July 2003. Samples were taken for $2\frac{1}{2}$ months using a staggered weekly schedule for the two varieties (Table 1). Two replicate plots for each variety were sampled. Experiment-defined maturity stages (1, 2, 3, 4, and 5) corresponded with duration of growing-season active growth of 96, 110, 124, 138, and 152 days and 103, 117, 131, 145, and 159 days for Alamo and Kanlow, respectively.

Switchgrass samples were transported within 30 min of sampling to a laboratory, where room conditions were maintained at a temperature of around 24 °C and relative humidity of about 65%. Samples gradually desiccated during storage to resemble processing conditions. Microbial growth such as mold was not visually observed on samples.

Table 1
Example of the weekly harvest and test schedule

Sun	Mon	Tue	Wed	Thu	Fri	Sat
—		A1	a1		a1	—
—	a1	K1	k1		a1/k1	—
—	k1	A2	a2	a1	k1/a2	—
—	a2	K2	k2	k1	a2/k2	—
—	k2	A3	a3	a2	k2/a3	—
—	a3	K3	k3	k2	a3/k3	—

'A*n*' indicates Alamo switchgrass harvest and strength test; 'a*n*' indicates Alamo switchgrass strength test day; 'K*n*' indicates Kanlow switchgrass harvest and strength test; 'k*n*' indicates Kanlow switchgrass strength test day; '*n*' ranged from 1 to 6 and corresponded with biweekly harvest group.

2.2. Test sample preparation

Separate switchgrass stem 2nd internodes were tested for ultimate tensile and shear stress, and moisture content was determined for corresponding 3rd internodes. Eight replicate samples per switchgrass variety were prepared for each tensile and shear test.

Preliminary tensile tests revealed that complete stem internodes were difficult to hold during force application. Gripping clamps crushed stem ends and introduced stress concentrations causing stem failures in the clamp. So, a new sample preparation method was developed to solve the gripping problem (Fig. 1). The 2nd internode of the hollow switchgrass stem was split into two halves along the longitudinal direction. A circular hole-puncher cut two small notches on opposing sides of the sample leaving a neck with width of about 1.65 mm. Notching was done at the middle section of split stems to ensure a controlled failure in the neck region. Non-split, small switchgrass stems were glued (cyanoacrylate) inside the inner radii of sample ends to reduce crushing by gripping chuck. Sandpaper strips were wrapped around the sample ends with abrasive inside to improve grip and to reduce stress concentration. The middle uncovered portion of the sample length was 25 mm and final overall lengths were trimmed to 50 mm (Fig. 1). Dimensions were measured with a digital micrometer with a resolution of 0.001 mm.

Shear test samples were simply sheared with no specific preparation, other than dimensional property measurements as described above.

2.3. Universal testing instrument

A universal testing instrument (MTS Alliance RT/30) applied and measured load-displacement characteristics and the ultimate failure loads of materials. A 1000-N capacity load cell mounted on the crosshead at an extension speed of 0.25 mm/min was selected. Effects of strain rate were not investigated, since typical biomass grinding occurs at a much higher rate than was available. TestWorks 4.05 of MTS Systems Corporation's testing