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Switchgrass ultimate stresses at typical biomass conditions available for processing

M. Yu, A.R. Womac*, C. Igathinathane, P.D. Ayers, M.J. Buschermohle

Department of Biosystems Engineering and Soil Science, The University of Tennessee, 2506 E.J. Chapman Drive, Knoxville, TN 37996-4531, USA

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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,

*Corresponding author. Tel.: +1 865 974 7104; fax: +1 865 974 4514.
E-mail address: awomac@utk.edu (A.R. Womac).

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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

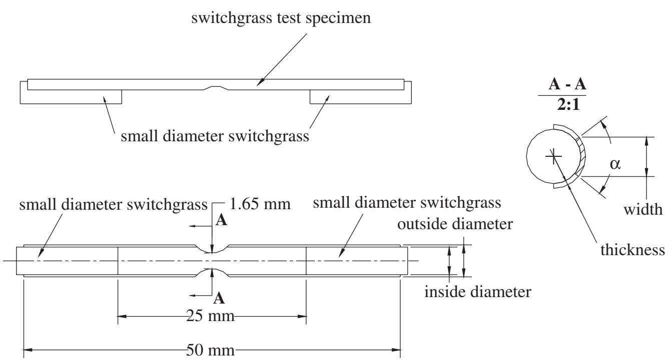

Fig. 1. Switchgrass specimen preparation for tensile test.

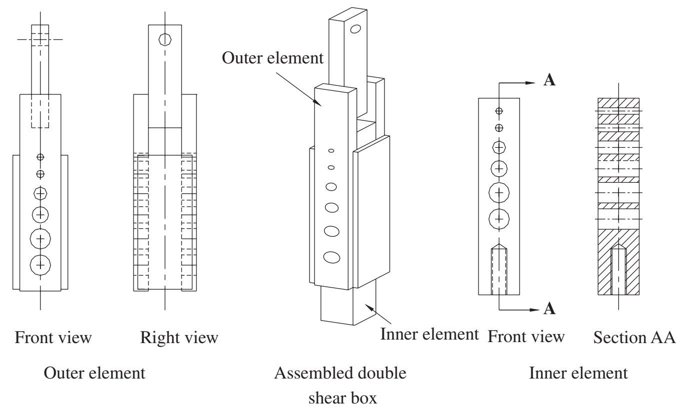

Fig. 2. Double shear box for applying shear stress to switchgrass stems.

software controlled the universal testing machine, data acquisition, and calibrations.

2.3.1. Tensile testing

Tensile force was longitudinally applied to prepared switchgrass stem samples. A three-jaw drill chuck gripped the sample top and was tightened first. A flat gripper held the sample bottom and was tightened last to not introduce twist and sample compression, unlike the drill chuck jaws that move outward when tightened.

Ultimate tensile failure stress (or ultimate tensile stress), σ, of the switchgrass stem sample was computed from maximum load acting normal on the minimum cross-section area (Fig. 1), where sample failure was visually verified. Ultimate tensile stress was calculated from the expression

$$\sigma = \frac{F_t}{A_t} \times 10^{-6}, \tag{1}$$

where σ is the tensile stress at failure, Mpa; F_t the tensile force at failure, N; and A_t the failure area of sample at notch, m^2.

The failure area of the neck portion of the sample was considered as rectangular and was estimated from width and thickness as

$$A_t = W \times T, \tag{2}$$

where W is the width of failure area of the sample, m, and T the average thickness of the switchgrass sample, m.

No attempt was made to calculate forces that would be required to fail whole stems in tension. Ultimate tensile stress is a basic material property and common basis to compare different materials and different stem diameters. Not all grinding is limited to single-cuts on whole stalks. Depending on resident time in the grinder and final particle sizes, particles being fractured during grinding can have partial cross-sections like those tested.

2.3.2. Shear testing

A double shear box (Fig. 2) was developed to apply shearing stress parallel to the applied load on two planes corresponding with the intersections of inner and outer elements on each side of the box. An internode was inserted into a through-hole, of size that most nearly matched stem diameter, without forced insertion. Hole diameters were 3.2, 4.8, 6.4, 9.5, and 12.7 mm.

Ultimate shear failure stress (ultimate shear stress) was determined using maximum shear load divided by the actual cross-sectional area of hollow switchgrass. Load was assumed equally distributed on the two failure planes. Ultimate shear stress was calculated from the expression

$$\tau = \frac{F_s}{2A_s} \times 10^{-6}, \tag{3}$$

where τ is the shear stress at failure, MPa; F_s the shear force at failure, N; and A_s the single failure area of sample, m^2.

Failure area of sample was calculated using the following equation:

$$A_s = \frac{\pi}{4}(D^2 - d^2), \tag{4}$$

where D is the switchgrass stem outside diameter, m, and d the switchgrass stem inside diameter, m.

2.4. Moisture content determination

ASAE Standards [17] for forage moisture measurement (air oven at 103 °C for 24 h) was used to determine moisture content of 3rd internodes. Switchgrass was harvested at about 60% wet basis (w.b.) moisture content and dried in the laboratory to about 10% w.b. after the last test period (386 h).

2.5. Data analysis

Statistical analysis was performed using SAS software [18]. Data were subjected to a one-way classification analysis of variance (ANOVA) with a 5% level of significance. Tukey–Kramer mean separation analysis was conducted to compare all possible pairwise mean combinations. Pearson correlations between combinations of the dependent and continuous independent variables were examined.

3. Results and discussion

3.1. Mean sample moisture content

Mean moisture contents of samples were 57%, 47%, 36%, 22%, 13%, and 11% (w.b.) for tensile and shear tests conducted at 2, 26, 74, 146, 242, and 386 h and 6, 30, 78, 150, 248 and 390 h after switchgrass harvest, respectively. Mean moisture contents over the duration of the experiment were steady at 38%, 34%, 34%, 37%, and 35% (w.b.) for maturity classes 1–5, respectively.

3.2. Ultimate tensile stress

Alamo variety had greater ultimate tensile stress than Kanlow ($P = 0.0091$), with mean values of 97.8 and 89.7 MPa, respectively. Range of published ultimate tensile stress for biomass materials compared to switchgrass are presented in Table 2. Switchgrass had a much higher ultimate tensile stress than that of other biomass crops published to date. Lowest values were similar among all biomass, whereas highest ultimate tensile stresses for switchgrass were up to five times greater than wheat straw at similar moisture content (10–65%). Results indicate that size reduction or grinding equipment that primarily apply tensile stresses to fail switchgrass will require much more grinding energy than wheat straw or rice straw. Grinding equipment that applies stresses other than ultimate tensile should be considered to reduce energy for size reduction.

3.3. Ultimate shear stress

Alamo variety had greater ultimate shear stress than Kanlow ($P = 0.0091$), with mean values of 20.5 and 17.9 MPa, respectively. Range of published ultimate shear stress for biomass materials compared to switchgrass are presented in Table 3. Lowest ultimate shear stresses between other biomass materials and switchgrass were similar. Highest ultimate shear stresses for switchgrass were higher than other biomass materials up to a factor of 5.7. Corresponding moisture content of published shear data spanned a much smaller range than tests conducted for switchgrass.

3.4. Comparison of ultimate tensile stress and ultimate shear stress

Mean ultimate tensile stress was significantly greater than mean ultimate shear stress ($P < 0.0001$). Ratios of mean ultimate tensile stress to mean ultimate shear stress were 4.77 and 5.00 for switchgrass varieties Alamo and Kanlow, respectively. Calculated ratios are similar to values reported for wheat straw of 4.32 for 1st internode and 4.30 for 4th internode [11]. Size reduction equipment may be much more efficient by applying shear stress rather than tensile stress, because shear mechanism may be considered the "weakest mode of failure" or "natural fracture point".

3.5. Effect of moisture content on ultimate tensile and shear stresses

Mean ultimate tensile stress decreased as mean moisture content increased for both Alamo and Kanlow varieties (Fig. 3). Mean ultimate shear stress did not show any clear trend with changes in moisture content (Fig. 4).

Halyk and Hurlbut [7] found that ultimate tensile and shear stresses of alfalfa were inversely proportional to moisture content. Greenberg et al. [14] reported that both ultimate stresses decreased with increasing moisture content for ryegrass. Annoussamy et al. [13] observed that shear strength increased as moisture decreased for wheat

Table 2
Biomass ultimate tensile stress comparison

Source	Biomass variety	Range of ultimate tensile stress (MPa)	Range of moisture content (%w.b.)
Limpiti [10]	Wheat straw	32.5–37.8	10–65
O'Dogherty et al. [11]	Wheat straw	22.7–31.2	8–22
Usery et al. [8]	Rice straw	14.8–17.8	58–79
Present study	Switchgrass Alamo	27.7–205	10–60
Present study	Switchgrass Kanlow	9.3–213	10–60

Table 3
Biomass ultimate shear stress comparison

Source	Biomass variety	Range of ultimate shear stress (MPa)	Range of moisture content (%w.b.)
Kushwaha et al. [9]	Wheat straw	7–22	5–30
		7–8	8–10
O'Dogherty et al. [11]	Wheat straw	5.14–6.55	8–22
Present study	Switchgrass Alamo	7.0–39.9	10–60
Present study	Switchgrass kanlow	6.9–38	10–60

straw. Ige and Finner [19] provided a similar result for corn stalk and alfalfa. They concluded that increased moisture content reduced shearing energy.

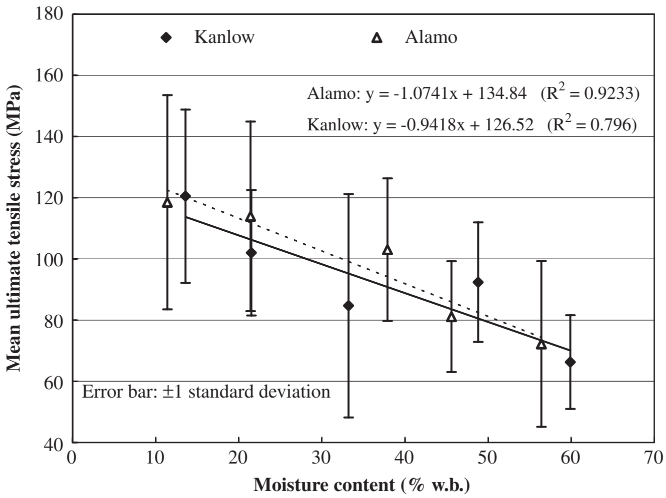

Fig. 3. Mean ultimate tensile stress versus moisture content for two switchgrass varieties.

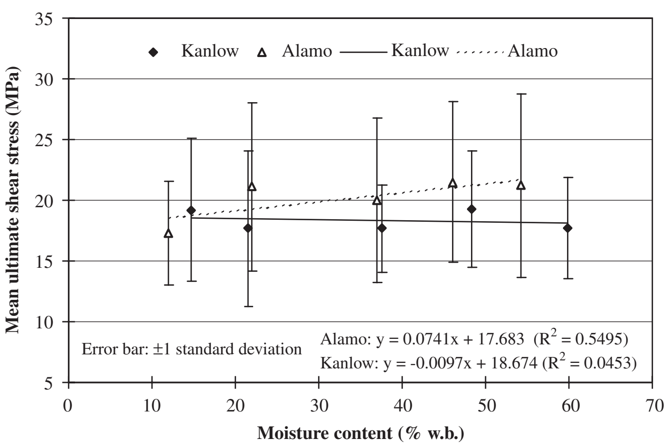

Fig. 4. Mean ultimate shear stress versus moisture content for two switchgrass varieties.

Others found an opposite trend. Kushwaha et al. [9] measured reduced shear stresses for wheat straw at low moisture ranging from 8% to 10% (w.b.). O'Dogherty et al. [11] also reported reduced shear stresses for wheat at moisture contents 8% and 10% (w.b.), and hypothesized that dry brittle straw was weaker than moist tough straw.

3.6. *Effect of maturity class on ultimate tensile and shear stresses*

Mean ultimate tensile stress slightly decreased with an increase in maturity class (Table 4) with a weak correlation coefficient (−0.16) with statistical significance ($P = 0.0009$) for pooled varieties. Mean ultimate shear stress decreased as maturity class increased (Table 4) with weak overall correlation coefficient of −0.19 and statistical significance ($P = 0.0000$) for pooled varieties. Weak correlations and no obvious trend between ultimate tensile and shear stresses and maturity class imply no advantage to either harvesting early or late in terms of applied stresses needed for size reduction.

3.7. *Effect of switchgrass stem and cross-section-preparation dimensions*

Stem diameter and wall thickness slightly decreased as time after harvest increased, and was attributed to shrinkage due to drying. Weak correlation coefficients were 0.24 ($P = 0.0000$) and 0.30 ($P = 0.0000$) between diameter and moisture and wall thickness and moisture, respectively.

Sample preparation was uniform throughout the experiment. Sample cross-section widths were not significantly different between switchgrass varieties ($P = 0.4356$) and between maturity classes of Alamo ($P = 0.1593$) and Kanlow ($P = 0.2278$). Consistent width of the sample neck section was one indicator of uniform manual sample preparation.

Table 4
Effect of maturity class on mean ultimate tensile and shear stresses for two switchgrass varieties

Maturity class	Mean ultimate tensile stress (MPa) (std. dev.)		Mean ultimate shear stress (MPa) (std. dev.)	
	Alamo	Kanlow	Alamo	Kanlow
1	92.7 B[a]	103.9 A	22.8 AB	19.9 A
	(38.0)	(35.01)	(7.6)	(5.9)
2	129.8 A	87.2 BC	24.5 A	15.5 C
	(33.2)	(23.4)	(8.2)	(4.6)
3	90.9 B	88.7 ABC	17.0 C	18.5 AB
	(28.1)	(28.3)	(4.3)	(5.6)
4	93.8 B	72.0 C	19.1 BC	19.2 AB
	(28.4)	(39.0)	(5.9)	(4.4)
5	91.3 B	94.2 AB	20.0 BC	17.0 BC
	(21.1)	(20.5)	(4.8)	(3.7)

[a]Uppercase alpha letters indicate column-wise mean separation.

4. Conclusions

Mean ultimate shear stress was approximately one-fifth of ultimate tensile stress for switchgrass. Thus, size reduction equipment that predominantly reduce particle sizes by shear failure, rather than tensile failure, are expected to be more energy efficient. Implementation of shear in a grinder includes, but is not limited to knives, shear bars, and mechanical pinch points that apply opposed-sliding actions to biomass. Mean ultimate tensile stress and shear stress were significantly different between switchgrass varieties, and differences may be encountered with other biomass feedstocks. 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% (w.b.). Future study should isolate whether the effect was due primarily to moisture or aging. Ultimate shear stress was relatively insensitive to elapsed time after harvest.

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