Shearing Characteristics of Biomass for Size Reduction

A.R. Womac,   M. Yu,   C. Igathinathane,   P. Ye,   and D. Hayes
University of Tennessee, Biosystems Engineering and Environmental Science, Knoxville, Tennessee

S. Narayan
First American Scientific Corp., Delta, British Columbia, Canada

S. Sokhansanj & L. Wright
Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Abstract. *A Warner-Bratzler shearing device in a universal test machine evaluated the cutting response characteristics of single stems of corn stover, hickory, and switchgrass. Different knife bevel angles (30° and 45°) at a fixed cutting speed of 254 mm/min were evaluated. Biomass cutting energy was determined on a stem cross-sectional area basis (specific cutting energy, kN/m). Biomass shear strength was based on peak load and actual cross-sectional area. Mean shear strengths due to cutting of corn stover, hickory, and switchgrass at 30° and 45° knife bevel angles were 1.8, 16.8, and 12.0 MPa, and 2.1, 24.9, and 12.5 MPa, respectively. Mean specific cutting energies for corn stover, hickory, switchgrass (10-15% moisture wet basis) were 28, 122, 78 kN/m, and 34, 160, and 95 KN/m for 30° and 45° knife bevel angles, respectively. Thus, the shallower 30° bevel angle required less cutting energy. In conclusion, unique characteristic load-displacement curves may not lead to easy development of biomass shear models. However, up to a 10-fold difference in shear strength was observed between corn stover and hickory wood, with hickory requiring larger stresses. It may be possible to identify categories based on biomass selections and shear strength to relate to biomass grinding energy. Optimum biomass cutting and equipment design, and the degree of potential improvement in biomass processing efficiency, may depend on the specific biomass application and condition.*

Keywords. Biomass grinding, bioprocessing, size reduction, biomass properties, switchgrass, hickory, corn stover, cutting energy

Introduction

Shear stress and energy properties of biomass influence the size reduction process. Identifying shear response of biomass may improve knowledge to improve grinder design and reduce grinding energy.

The objective of the research herein was to identify shearing characteristics of three biomass materials, namely corn stalk, hickory wood, and switchgrass.

Experimental Methods

Machine Description

A Warner-Bratzler shear fixture (Figure 1) in the universal testing machine Alliance RT/30 evaluated the shearing response characteristics of biomass for size reduction. A 6500-pound capacity load cell (100942) was mounted to the crosshead. TestWorks 4.05 software controlled the test equipment and recorded data.

The Warner-Bratzler shear fixture included 3.2-mm thick stainless steel blades with a 60° V-shaped notch. Notch radius was 1.6 mm. Two knife bevel angles (30° and 45°) were precision ground on individual knives. Knife sharpness was monitored and will be reported elsewhere. The knife blade passed through a groove in a base plate that supported the biomass sample. Cutting distance was no more than sample radius times three (Figure 1). On occasion, brittle samples of hickory wood and switchgrass fractured at a displacement less than sample radius times three.

A stainless steel adapter connected the notched blade to the load cell. The base fixture of the universal test machine supported the base plate of the shear fixture. This design provides alignment of the fixture and allows rapid changes. The Warner-Bratzler shear test produces a cutting shear action as the V-blade was forced through the specimen.

Stainless steel blade with a 60° V-shaped notch

sample cross section
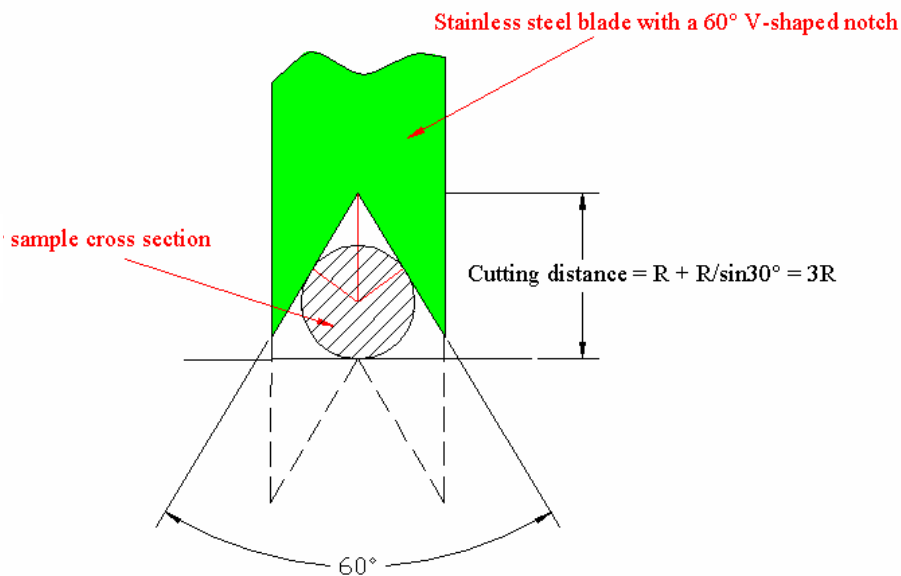
Cutting distance = R + R/sin30° = 3R

60°

Figure 1. Diagram of knife-sample geometry and maximum cutting distance used to integrate cutting energy from load-displacement curves. R is defined as the sample radius.

Materials Selection and Preparation

Corn stover, hickory wood, and switchgrass were used as specimens for this test. Samples were prepared so that pair wise comparisons were performed within the same internode region for 30° and 45° knife bevel angles. Moist (or fresh) and dry samples were used when possible (Table 1).

Table 1 Physical properties for different test biomass

Biomass variety	Average diameter (mm)	Moisture content (%w.b.)
Dry corn stover	18.9	~ 9%
Moist corn stover	19.0	~ 75%
Dry hickory wood	9.2	~ 13%
Fresh hickory wood	10.9	~ 35%
Dry switchgrass	3.2	~9%

Shear Testing

Physical dimension, moisture content, and shearing force-displacement curves for each biomass stem sample were determined. A fixed crosshead speed of 254 mm/min was selected. Experimental shear rate was much lower than actually occurring within a typical grinder, but the experiment offered insight into fundamental shear characteristics.

Biomass shear strength was based on peak load and actual cross-sectional area. The shear failure stress (or ultimate shear stress, MPa), τ, of the specimen was calculated from the expression:

$$\tau = \frac{Fs}{A}$$

where:

τ - shear stress at failure, Pa.

Fs - shear force at failure, N

A - area of actual failure cross-sections, m^2.

Biomass cutting energy was determined on a stem cross-sectional area basis (specific cutting energy, kN/m). Energy was calculated by integrating the force displacement curve through the cutting distance.

Moisture Content Testing

Moisture content was determined for each tested sample using a convection oven method. According to the ASAE standards, a representative sample of at least 25 g was selected. Sample moisture content was obtained by subjecting a sample to oven drying at 103°C for 24 h.

Results

Characteristic Load-Deformation Responses

Sample load-displacement curves are shown in Figures 2-5 for various biomass selections below:

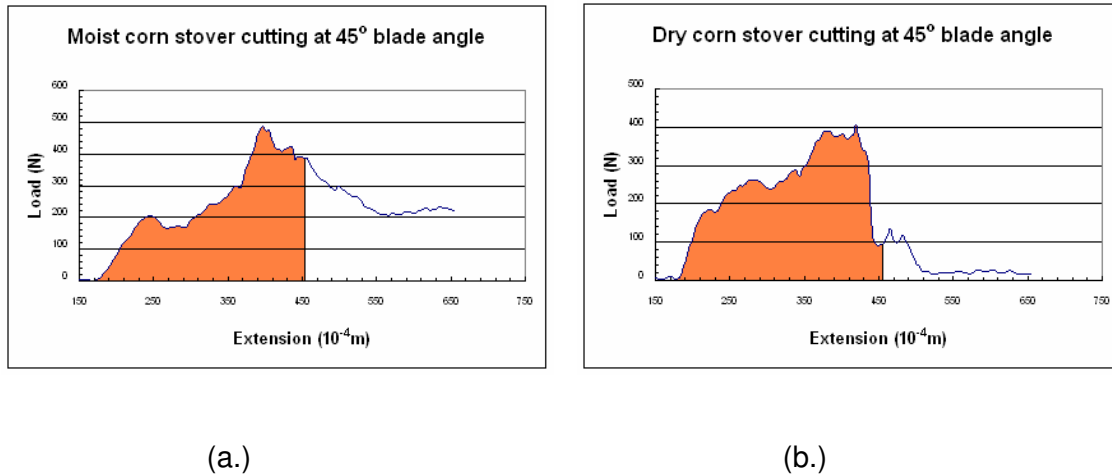(a.)   (b.)

Figure 2. Sample load-displacement curves for corn stover with moisture content of (a.) ~75% w.b. and (b.) ~9% w.b. using 45° knife bevel angle. Shaded portion represents shear energy integration using cutting distance.

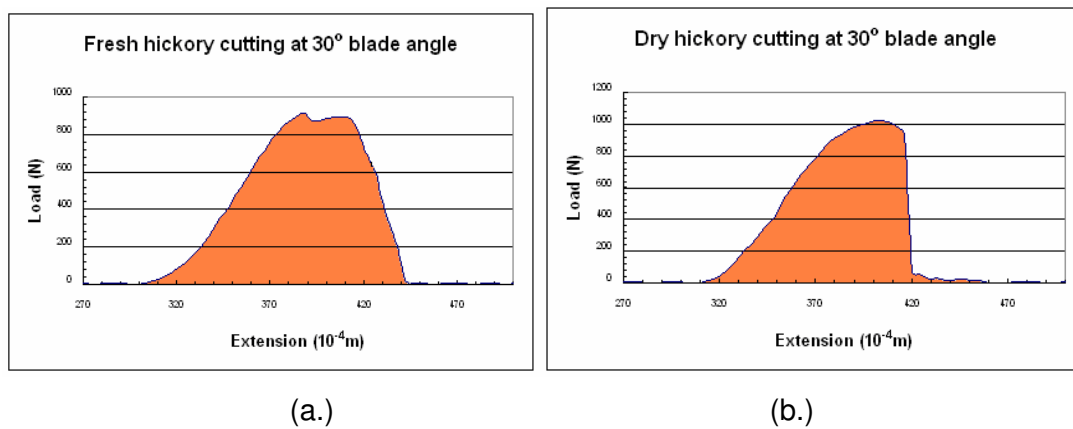(a.)   (b.)

Figure 3. Sample load-displacement curves for hickory wood with moisture content of (a.) ~35% w.b. and (b.) ~13% w.b. using 30° knife bevel angle. Shaded portion represents shear energy integration using cutting distance.
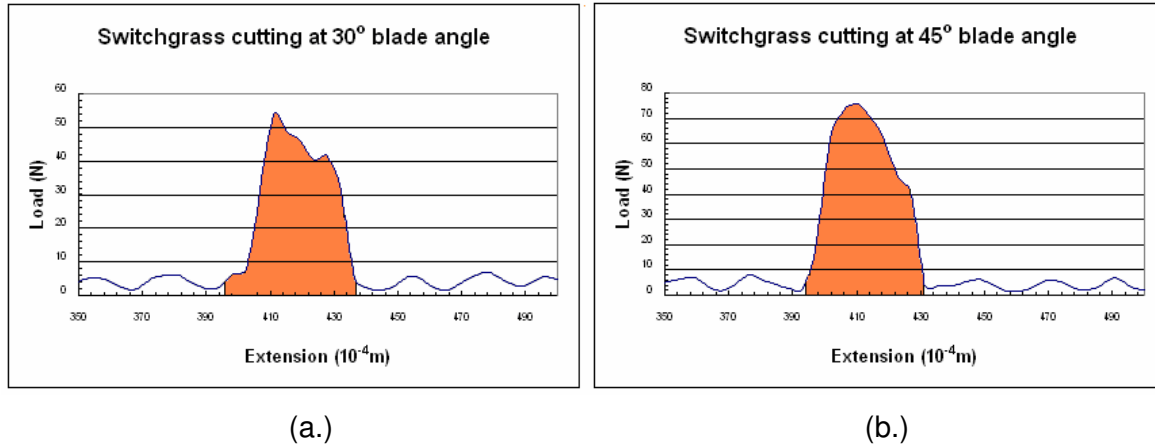
(a.)   (b.)

Figure 4. Sample load-displacement curves for switchgrass with moisture content of 13% w.b. using (a.) 30° and (b.) 45° knife bevel angles. Shaded portion represents shear energy integration using cutting distance.
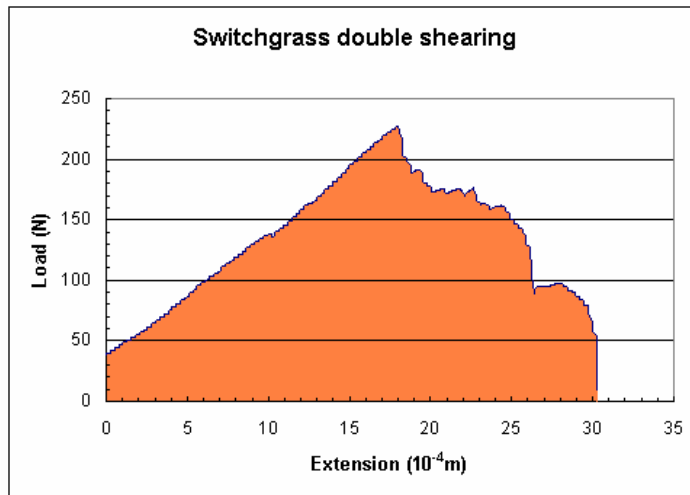

Figure 5. From a previous switchgrass study that used a hole-type shear box. Shaded portion represents shear energy integration.

Shear Strength and Cutting Energy

Shear strengths were statistically different ($p < 0.001$) for three dry biomass materials at the given knife bevel angles. Mean shear strengths due to cutting of corn stover, hickory, and switchgrass at 30° and 45° knife bevel angles were 1.85, 16.77, and 12.04 MPa, and 2.08, 24.92, and 12.46 MPa, respectively (Table 2). Thus, the 30° knife required 11, 33, and 3% less mean shear strength than the 45° knife for each material. Dry hickory wood and dry switchgrass shear strength value are 8~10 and 6 fold greater than corn stover at both 30° and 45° bevel angles. Therefore, dry corn stover is much easier to cut than the other two dry biomass materials. Shear strengths were statistically the same ($p = 0.58$) at different bevel angles for dry switchgrass at a moisture content of ~9% w.b.

Biomass variety (dry) significantly ($p < 0.001$) affected cutting energy for both knife bevel angles. Mean specific cutting energies for corn stover, hickory wood, and switchgrass were 27.94, 121.99, and 78.00 kN/m, and 34.19, 160.07, and 95.20, kN/m for 30° and 45° knife bevel angles, respectively (Table 1). Thus, the shallower 30° bevel angle required less cutting energy when cutting corn stover, hickory, and switchgrass. Dry hickory wood cutting energy for both knife bevel angles were ~1.5 times greater than dry switchgrass and ~ 4 times greater than dry corn stover. Dry switchgrass cutting energy for both knife bevel angles were ~2.8 times greater than dry corn stover. Cutting energy was significantly different ($p = 0.04$) at different bevel angles for dry switchgrass at a moisture content of ~9%.

Table 2. Mean shear strengths and cutting energy for three biomass materials with moisture content ranging from ~9-~13% w.b.

Biomass Property	Biomass Variety and Blade Angle (°)					
	Corn Stover (dry)		Hickory (dry)		Switchgrass (dry)	
	30°	45°	30°	45°	30°	45°
Mean Shear Strength (MPa) (Std.Dev.)	1.85Ac (0.61)	2.08Ac (0.52)	16.77Aa (1.13)	24.92Ba (2.91)	12.04Ab (0.53)	12.46Ab (0.53)
Mean Cutting Energy (kN/m) (Std.Dev.)	27.94Ac (5.65)	34.19Bc (6.80)	121.99Aa (11.69)	160.07Ba (12.73)	78.00Ab (10.88)	95.20Bb (22.51)

[1]Uppercase letters indicate column-wise mean separation for different bevel angles in the same group of biomass materials.

[2]Lowercase letters indicate column-wise mean separation for the same bevel angles in the different group

For fresh hickory wood at moisture content ~35%, shear strengths were statistically different ($p < 0.001$) at the given knife bevel angles. Mean shear strength due to the cutting of hickory by 30° and 45° knife bevel angles were 10.94 and 13.41 MPa respectively (Table 3). For the dry hickory wood at moisture content 11~15%, shear strengths were also statistically different ($p < 0.001$) at the given knife bevel angles. Mean shear strength due to cutting of hickory by 30° and 45° knife bevel angles were 16.77 and 24.92 MPa respectively. For both fresh and dry hickory wood biomass material, the shearing strength at 30° knife bevel angles was less than 45° bevel angles. Mean shear strength due to cutting of hickory of different bevel angles were significantly different ($p < 0.001$) for fresh material and dry material. Dry hickory wood had greater shear strength value than fresh hickory wood by both bevel angles. Therefore, the dry hickory wood is more difficult to cut than fresh hickory wood.

Cutting energy at both knife bevel angles were significantly different for dry hickory wood ($p < 0.001$) and fresh hickory wood ($p = 0.003$). Mean specific cutting energies for dry hickory were 121.99 kN/m and 160.07 kN/m for 30° and 45° knife bevel angles, respectively. Mean specific cutting energies for fresh hickory were 91.60 kN/m and 114.31 kN/m for 30° and 45° knife bevel angles, respectively. Thus, the shallower 30° bevel angle required less cutting energy when cutting both dry and fresh hickory wood. Mean cutting energy of hickory by

different bevel angles are significant different (p < 0.001) for fresh material and dry material. Dry hickory wood required more shear energy than fresh hickory wood by both bevel angles.

Table 3. Mean shear strengths and cutting energy for dry/fresh hickory wood

Biomass Property	Biomass and Blade Angle (°)			
	Hickory (fresh)		Hickory (dry)	
	30°	45°	30°	45°
Mean Shear Strength (MPa) (Std.Dev.)	10.94Aa (1.06)	13.41Ba (1.13)	16.77Ab (1.13)	24.92Bb (2.91)
Mean Cutting Energy (kN/m) (Std.Dev.)	91.60Aa (9.42)	114.31Ba (19.07)	121.99Ab (11.69)	160.07Bb (12.73)

[1]Uppercase alpha letters indicate column-wise mean separation for different bevel angles in the same group

[2]Lowercase alpha letters indicate column-wise mean separation for the same bevel angles in the different group

For the moist corn stover at moisture content ~75%, shear strengths were statistically the same (p = 0.615) at the given knife bevel angles. Mean shear strength due to cutting of corn stover at 30° and 45° knife bevel angles were 2.11 and 2.01 MPa, respectively (Table 4). For the dry corn stover at moisture content ~9%, shear strengths were also statistically the same (p = 0.215) at the given knife bevel angles. Mean shear strength due to cutting of corn stover at 30° and 45° knife bevel angles were 1.85 and 2.08 MPa respectively. For both moist and dry corn stover biomass material, the shearing strengths are the same (p=0.286) at 30° bevel angles, and are the same (p=0.7455) with 45° bevel angles.

Cutting energy at both knife bevel angles for moist corn stover is significantly different (p < 0.001). Mean specific cutting energies for dry corn stover were 25.31 KN/m and 33.14 KN/m for 30° and 45° knife bevel angles, respectively. Thus, the shallower 30° bevel angle required less cutting energy when cutting moist corn stover. Cutting energy at both knife bevel angles for dry corn stover is significantly different (p = 0.038). Mean specific cutting energies for dry corn stover were 27.94 kN/m and 34.19 kN/m for 30° and 45° knife bevel angles, respectively. Thus, the shallower 30° bevel angle required less cutting energy when cutting dry corn stover either. Mean cutting energy of moist and dry corn stover are statistically the same (p > 0.2029) at 30° bevel angles and the same with p>0.7654 at 45° bevel angles.

Table 4. Moist and dry corn stover mean shear strengths and cutting energy

Biomass Property	Biomass and Blade Angle (°)			
	Corn Stover (Moist)		Corn Stover (Dry)	
	30	45	30	45
Mean Shear Strength (MPa) (Std.Dev.)	2.11A**a** (0.40)	2.01A**a** (0.40)	1.85A**a** (0.61)	2.08A**a** (0.52)
Mean Cutting Energy (kN/m) (Std.Dev.)	25.31A**a** (2.77)	33.14B**a** (4.47)	27.94A**a** (5.65)	34.19B**a** (6.80)

[1]Uppercase alpha letters indicate column-wise mean separation for different bevel angles in the same group

[2]Lowercase alpha letters indicate column-wise mean separation for the same bevel angles in the different group

Conclusions

1. Characteristic load-displacement curves were determined by biomass selection, moisture content, and shear loading device for a quasi-static test. Difficulty in pinpointing exact failure stress and energy may lead to difficulty in modeling shear under dynamic conditions in a grinder.

2. Up to a 10-fold difference in shear strength was observed between corn stover and hickory wood, with hickory requiring larger stresses. It may be possible to identify categories based on biomass selections and shear strength to relate to biomass grinding energy.

3. Knife bevel angle influenced failure stress and energy generally for biomass with increased strength (i.e. hickory wood). Importance of improving grinder design may depend on the relative strength of biomass being ground.

4. Moisture content of biomass influenced failure stress and energy generally for biomass with increased strength (i.e. hickory wood). Importance of managing timing of grinding relative to moisture content may depend on the relative strength of biomass being ground.

5. Optimum biomass cutting and equipment design, and the degree of potential improvement in biomass processing efficiency, may depend on the specific biomass application and condition.