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Effect of moisture content and dimensional size on the shearing chararacteristics of sugarcane stalks

Javad Taghinezhad*, Reza Alimardani and Ali Jafari*

Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology University of Tehran, P.O. Box 4111, Karaj 31587-77871, Iran

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Abstract The mechanical cutting properties of sugarcane stalks were studied using a linear blade cutting and UTM device to determine of the effect of sample moisture content with respect to the cutting element and quantify the possible cutting energy reduction. Also the effect of the dimensional parameters on mechanical cutting properties were studied on small, medium and large size for cutting force, energy, ultimate stress, and specific energy of sugarcane stalks. The device was used along with a universal test machine that quantified shearing stress and energy characteristics for applying force on sugarcane stalks through a blade device. Mean specific cutting energies of cane stalks at low, medium and high levels of moisture content were 34.071, 28.339 and 16.297 kN/m and for ultimate stress were 7.086, 2.586 and 1.656 MPa, respectively. Also other parameters of mechanical cutting such as energy and peak force were presented and the results showed a significant difference between levels of moisture content and dimensional parameters in mechanical cutting properties. The high moisture content level compared to low moisture content level produced a significant reduction in the ultimate stress and the specific energy by about one-second.

Key words: Mechanical cutting, moisture content, Sugarcane stalk, ultimate stress, Cutting energy.

Introduction

Sugarcane (*Saccharum officinarm L.*) is an important raw material for the sugar industries (Frank, 1984). Sugar cane is a perpetual agricultural crop grown primarily for the juices extracted from its stalks. Raw sugar produced from these juices are later refined into white sugar. As a perennial crop, one planting of sugarcane will generally allow for three to six or more annual harvests before replanting is necessary. In Iran, sugar cane is widely cultivated on an area of about 68352 ha with an annual production of about 5685090 ton (FAO, 2010).

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* **Corresponding author**: Reza Alimardani; **e-mail:** rmardani@ut.ac.ir

Most investigations on the mechanical properties of plants have been performed during their growth using failure criteria (force, stress and energy). Studies have focused on plant anatomy, lodging processes, harvest optimization, animal nutrition, industrial applications and the disintegration of sugarcane stalk in soil (McNulty and Moshenin, 1979; Annoussamy et al, 2000; Skubisz et al, 2007).

Compression, tension, bending, shearing, density and friction are the important properties of the cellular material in cutting. These properties depend on the species, variety, stalk diameter, maturity, moisture content and cellular structure (Bright and Kleis, 1964; Persson, 1987). These physical properties are also different depending on the heights of the plant stalk and loading rates (Mohsenin, 1963).

Shearing was shown to be an energy-efficient method of size reduction, and was achieved by devices that used knives, shear bars, and linear knife grids with ram (Igathinathane et al, 2008; Igathinathane et al, 2009).

Particular works have been carried out to specify the mechanical properties of plants. Kushwaha et al. (1983) reported mean values of shear strength of wheat straw in the range of 8.6-13.0 GPa with some dependence on moisture content. Dernedde (1970) used a shear box method to measure shear strength of different varieties of tested forage materials singly. In two series of experiments, he found ranges of 25–88 MPa and 59–128 MPa, with maximum at moisture contents of 20 % w.b. and 35 % w.b. for the two sets of data. The shape of the curves relating shear strength to moisture content were analogous to those found by Liljdall et al. (1961) who investigated the specific energy required to cut beds of forage. Other researchers have measured the specific energy required to shear materials. Shinners et al. (1987) found that longitudinal shearing of alfalfa stems required less than 10 % of the energy to shear alfalfa transversely. Tavakoli et al (2009) studied on the effect of moisture content and loading rate on the shearing characteristics of barley straw by internode position they found the shear strength varied from 3.68 to 6.18 MPa, and the shearing energy ranged from 65.17 to 131.06 mJ for barly straw.

McRandal and McNulty (1980) conducted shearing experiments on field grasses and found that the mean shearing stress was 16 MPa and the mean shearing energy was 12.0 mJ.mm-2. Prasad and Gupta (1975) found that the cross-sectional area and moisture content of the crop had a significant effect on the cutting energy and the maximum cutting force. Similar results were also reported by Choi and Erbach (1986). Sakharov et al. (1984) reported that the required force to cut stretched (bent) stalks was 50 % less than that for straight stalks.

The objective of the research herein was to identify the effect of moisture content of sugarcane stalks on the cutting process with respect to the knife cutting plane. Therefore, to determine the mechanical cutting strength properties of sugarcane stalks, peak force, peak energy, total energy, ultimate failure stress, and energy per unit area were measured. Results of this research will determine the variation in mechanical cutting strength properties and quantify the benefits of material (wet or dried) in cutting.

Material and methods

Experimental sugarcanes for tests

Sugarcane stalks were harvested in October, 2011 from a field in Debel Khazaie, Ahvaz, Iran and were transferred to the Physical Properties of Materials Laboratory, Department of Agricultural Machinery Engineering, Faculty of Engineering and Technology, University of Tehran, Karaj, Iran. The stockpile sugarcane was stored (1 months) indoors until the experiments were carried out in a laboratory having air conditions of about 25 ° C and relative humidity of about 55%, where the canes naturally dried and balanced with the current ambient conditions. No degradation of the canes was observed after the field rise and the indoor storage, as the canes had maintained their structural integrity as was evident during material preparation cuts of the canes. 45 samples of sugarcane stalks of approximate length of 5 cm were cut using a bandsaw with fine blade for tests.

Moisture content measurement

In order to investigation of moisture content effect on sugarcane stalks' mechanical cutting properties, samples were prepared in three level of moisture content. Thus to approach the higher moisture level, sugarcane stalks must be placed near the vapor of water, so the samples were placed in saturated air in an isolated box at 30˚C for 24 hours. To achieve the lower moisture content level, the oven method was used at 103˚C for preparing low level of moisture content with time duration of 48 hours. And normal balanced sugarcanes were used for middle level of moisture content.

Measurement of sample dimensions, weight and area

Diameter

A digital vernier caliper with ±0.01 mm accuracy and 15 cm potential of maximum reading was used for measuring the minor and major canes diameters. As the shape of canes was a tapered elliptical cylinder (Igathinathane et al, 2006) the cross section profile of the canes was an ellipse. The dimensions of the major (D_1- cross-sectional width) and minor (D_2 - cross-sectional thickness) axis of the elliptical cross section were measured before testing and the estimated values were recorded.

Weight

The weights of the blade and stalk samples were recorded using weight balance with an accuracy of ± 0.01 g.

Area determining

From the major and minor diameter the cut sectional areas were determined according to the following geometric formulae:

$$A_p = \left(\frac{\pi}{4}\right) D_1 \times D_2 \qquad (1)$$

where: A_p is the cut area created when the blade is perpendicular to the cane axis (mm^2), i.e. across the sample; D_1 is the major-axis of the elliptical cross section of the cane (mm); D_2 is the minor-axis of the elliptical cross section of the cane (mm).

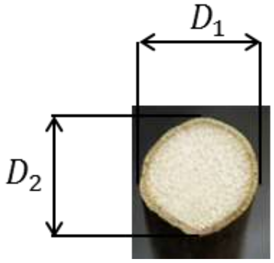


Fig. 1. Sugarcane stalk and its axis.

The shearing device

The shearing device selected was originally used for cutting stalks of crops in a harvest machine that used in the commercial sugarcane choppers. The blade was sharpened and used as cutting tool in shearing device developed (Fig. 1). The cutting edge was given a single slant angle of 30 ° that caused energy efficient cuts (Womac *et al.*, 2005) and the notch angle was 60 °(Fig. 1).

The triangular notch of the blade self-centered the samples during cutting. The blade freely passed through the groove of the fixture that served as a platform to hold the sample (Fig. 1).

A proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Karaj, Iran, 2007) was used as the measurement platform (Fig.2) in combination with a modified shearing device (Mahmoodi and Jafari, 2010). The cutting blade was fixed in a movable clamp and the fixture was fixed in a fixed clamp and the tests were performed.

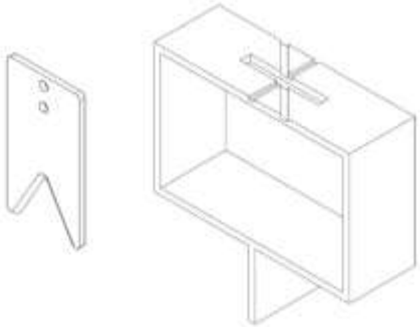


Fig.1. The cutting blades device and a view of fixture that used for fixing samples.

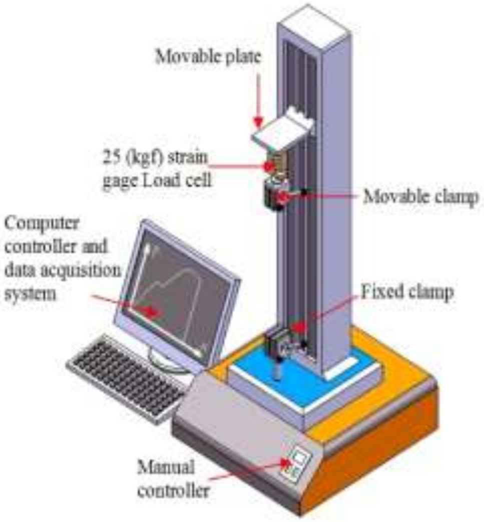


Fig. 2. Instron Universal Testing Machine (Instron UTM/ SMT-5, SANTAM Company, Tehran, Iran)

Data collection and analysis

The Instron UTM plotted the force-displacement parallel to the cutting characteristics of the cane samples at different sizes and orientations. Regularly, the total cutting energy consumed was appraised from the original data stream of the force-displacement characteristics using the following expression:

$$E_t = \left(\sum_{m=1}^{n} \frac{(y_{m+1} + y_m)}{2}\left(x_{m+1} - x_m\right)\right)_{samples} - \left(\sum_{m=1}^{n} \frac{(y_{m+1} + y_m)}{2}\left(x_{m+1} - x_m\right)\right)_{idle} \qquad (2)$$

where: E_t is the total cutting energy (Nm); y_m is the force at any instant m (N); x_m is the deformation at any instant m (m); and n is the total number of observations of the force-displacement data.

As the cutting blade had enough clearance and moved without limits through the groove, the idle energy part of Eq. (2) was neglected. Furthermore, the software prepared for UTM was scheduled in advance Of output the peak load, peak energy, and total energy directly from the force-displacement characteristics. From these results, the ultimate cutting stress and specific energy were calculated from the cut sectional areas as:

$$\tau_u = \frac{F_{sp}}{A} \qquad (3)$$

$$E_{ts} = \frac{E_t}{A} \qquad (4)$$

where: τ_u is the ultimate cutting stress (Pa); F_{sp} is the peak cutting force (N); A is the cut sectional area (Eqs. (1)); E_{ts} is the total specific energy (N m^{-1}); and E_t is the total energy consumed in cutting the canes (N m).

Experimental

For studying relationship between moisture content and mechanical strength parameters 45 samples of sugarcane stalks with multiple thicknesses were selected between stalks and tested by Instron UTM with 10 mm/min loading rate. The stalk was laid on its side and cutting was parallel to the major axis. After preparing of samples force and consumed energy for cutting of each sample was measured and this work repeated for three levels of moisture contents. For weighting samples digital balance with ± 0.01 gr accuracy was used. Finally samples kept in oven at 103˚C for 72 hours to determining the absolute moisture content of samples in each level. . Moisture content (M.C) was computed on wet basis by Eq.5.

$$M.C\% = \frac{w_w}{w_d} \times 100 = \frac{w_i - w_d}{w_d} \times 100 \qquad (5)$$

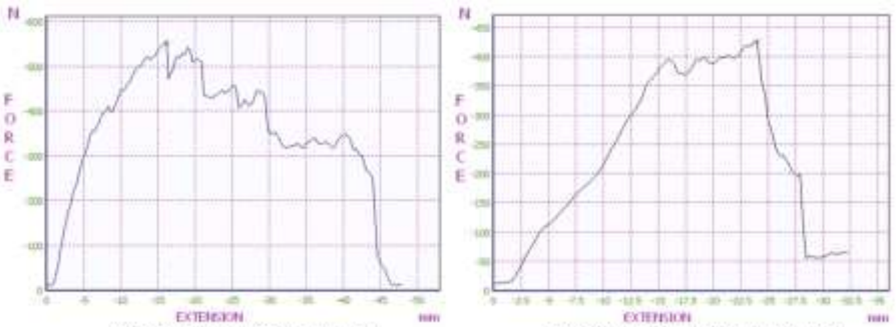
where w_i is the initial weight of sample, w_w is the weight of sample water and w_d is the weight of dried sample. The moisture content levels 0-10, 10-50 and 50-75 % were selected as low, middle and high moisture content levels for samples.

The SPSS software (2007) was used to determine the effect of size, sample material variation, and orientation on various mechanical strength parameters involved in cutting the cane samples.

Results and discussions

Sugarcane cutting force-deformation characteristics

Representative force-deformation characteristics of prepared sugarcane stalks at different levels of moisture content are presented in Fig. 3. Comprehensively, the force-deformation curves showed an initial extreme rise of cutting force, followed by an initial high peak, a quick drop, a second peak, and finally an insignificant force after the sample cutting. Due to the high moisture content of the material in tests, force-displacement curves indicated a wide base and peak also with decrement in the level of moisture content steeply rise and sudden drop in curves accrued. Difference in analytical components (high, middle or low moisture content sample) manifested clearly as distinct force-deformation characteristics (Fig. 3). Since the low moisture content samples were brittle, the force-deformation curves of low moisture content samples were steep with narrower base; unlike flexible high moisture content samples curves differentiated by wider peak and base.



High moisture content sample

Medium moisture content sample

Low moisture content sample

Fig. 3. Force-displacement curves of cutting sugarcane stalks in different levels of moisture content.

Igathinathane et al (2010) studied corn stalks and reported that the force-displacement is divided into five perceptible regions: 1- Compression of stalks by the blade. 2- Initial cutting. 3- Progress of skin and pitch cutting. 4- Final cutting of skin 5- Completion of cutting and residual force (Fig. 4).

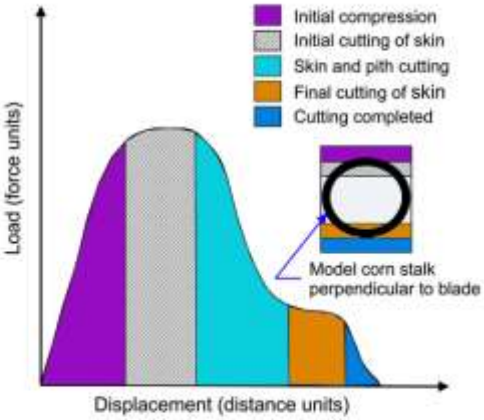


Fig. 4. Distinct regions of the stalk cutting force-displacement characteristics (Igathinathane *et al*., 2010)

After accomplishing the cutting tests, the data were obtained for statistical analyses and force-deformation curves.

Mechanical cutting analysis

In Table 1, the mechanical cutting was evaluated as a function of sugarcane samples moisture content during the tests. The internodes tests on different level of moisture contents (low, medium, and high) of sugarcane stalks samples showed that the dimensional parameters are significantly different in different moisture content level. In low level of moisture contents the value of dimensional parameters decreased because the main volume of sugarcanes contains from water. Although, it can be revealed that peak force and energy for low level are different from two others, ultimate stress and specific energy for mechanical cutting of samples vary significantly ($P < 0.05$) on overall basis (Table 1) between three levels. The ultimate stress of the sugarcane stalks decreased from 7.086 to 2.948 MPa, and 1.565 MPa respectively, as the moisture content increased (Fig. 5). Also the specific energy of the sugarcane stalks decreased from 34.071 to 28.339 kN m^{-1}, and 16.297 kN m^{-1} for the low, medium and high levels of sugarcane stalks moisture content respectively (Fig. 6).

Table 1. Effect of moisture content of the sugarcane stalks on the mechanical cutting parameters

Level of moisture content	**D$_1$**	**D$_2$**	**Peak force (N)**	**Energy (kN m)**	**Ultimate stress(MPa)**	**Specific energy (kN m^{-1})**
Low	13.73±4.59a	14.60±3.6a	955.15±241.80a	4761.4±1385.6a	7.086±2.948a	34.071±12.30a
Medium	16.95±3.22b	16.59±2.95b	564.81±165.72b	6150.2±1873.7b	2.586±0.541b	28.339±6.961b
High	21.73±3.06c	21.96±3.97c	601.88±171.56b	6117.4±2474.7b	1.656±0.455c	16.297±4.280c

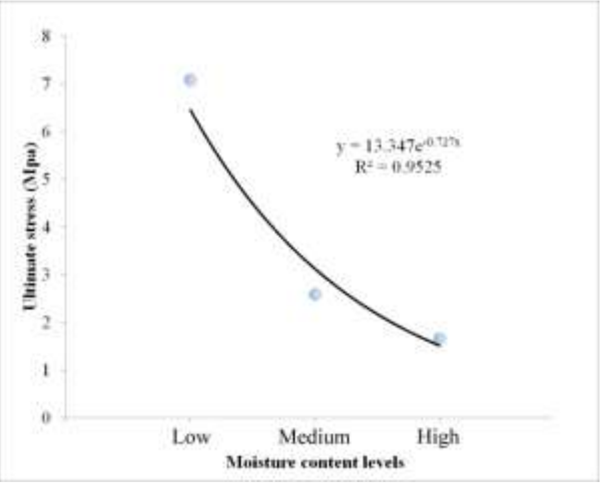


Fig. 5. Effect of moisture content of sugarcane stalks on the ultimate stress

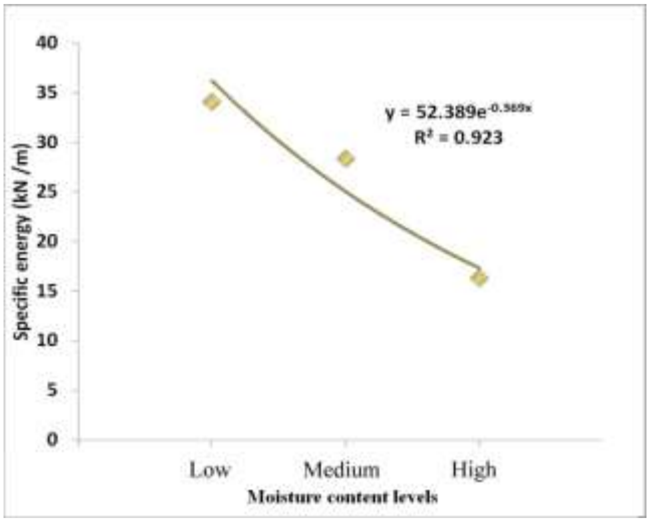


Fig. 6. Effect of moisture content on the specific shearing energy

Mechanical cutting analysis with respect to dimensional parameters

The mechanical cutting was evaluated as a function of sugarcane samples moisture content levels with respect to stalks size and the cross sectional area used as a parameter to describe stalk size. Various mechanical strength properties were compared statistically among different sizes and between moisture content levels (Table 2).

Table 2. Effect of the sugarcane stalks size on the mechanical cutting parameters in different moisture content levels

Level of moisture content	**Size**	**Area**	**Peak force (N)**	**Energy (kN m)**	**Ultimate stress(MPa)**	**Specific energy (kN m^{-1})**
Low	Small	78.99±10.5Aa	814.05±192.32aA	3427.5±577.1aA	10.226±1.448aA	44.178±0.814aA
	Medium	12.84±19.68bA	969.21±113.44bA	5115.1±1171.4bA	7.785±0.93bA	40.744±7.439bA
	Large	278.38±25.37cA	1054±3421.3cA	5474.7±1430.4cA	3.874±1.565cA	26.226±7.753cA
Medium	Small	146.25±15.24aB	422.73±99.55aB	4705.6±1058.8aB	2.895±0.634aB	32.274±6.879aB
	Medium	214.59±9.22bB	578.03±62.28bB	6419.6±1647.4bB	2.689±0.186bB	29.756±6.627bB
	Large	314.37±13.86cB	698.96±150.59cB	7433±1826cB	2.215±0.402cB	23.554±5.16cB
High	Small	235.62±66.64aC	471.14±63.98aC	4091.7±853.92aC	2.068±0.364aC	17.657±1.553aC
	Medium	372.9±47.26bC	589.17±82.78bC	6137.1±896.86bC	1.615±0.39bC	16.780±3.849bC
	Large	478.39±42.98cC	690.49±225.74cC	7317.1±3316cC	1.4417±0.450cC	15.094±5.885cC

The moisture content had a significant effect ($P<0.05$) on the peak force and shearing energy as shown in Table 2. The peak force and shearing energy increased with an increase in the size of stalks in each level of moisture content similar results have been reported by most previous researchers (McRandal and McNulty, 1980; Announssamy, 2000). But between levels of moisture content with an increase in moisture content of sugarcane stalks peak force and shearing energy decreased. In Table 2 dissimilar lower case group labels (a, b, and c) represent a significant difference ($P < 0.05$) among size category; and dissimilar upper case group labels (A, B, and C) represent a significant difference ($P < 0.05$) between level of moisture content.

To understand better the influence of material moisture content changes in the ultimate stress and specific cutting energy, the material size changes were studied in three sizes for each level of moisture content. The results of those experiments can be seen in Fig. 7 and Fig 8.

In each level of moisture content the ultimate stress and specific energy of the sugarcane stalks mechanical cutting decreased clarity, as the size of cutting section increased (Fig. 7 and Fig. 8). Also this can be indicated that these parameters values decreased with increasing in moisture content levels of sugarcane stalks from the low, medium and high levels respectively (Fig. 7 and Fig. 8).

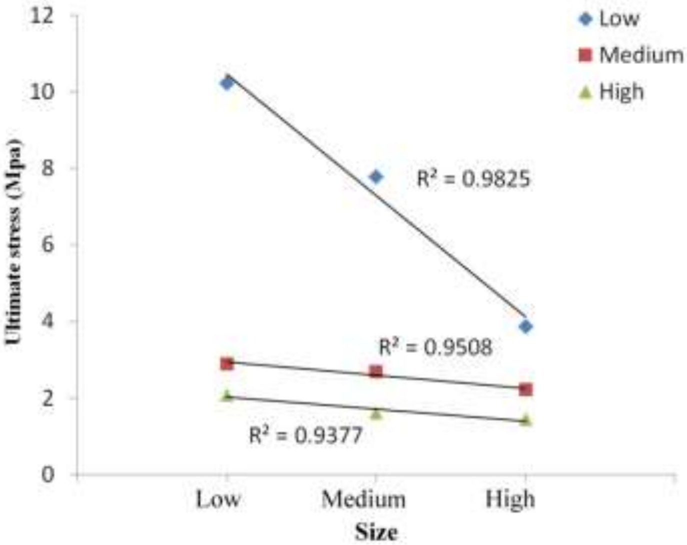


Fig. 7. Effect of moisture content and size of sugarcane stalks on the ultimate stress

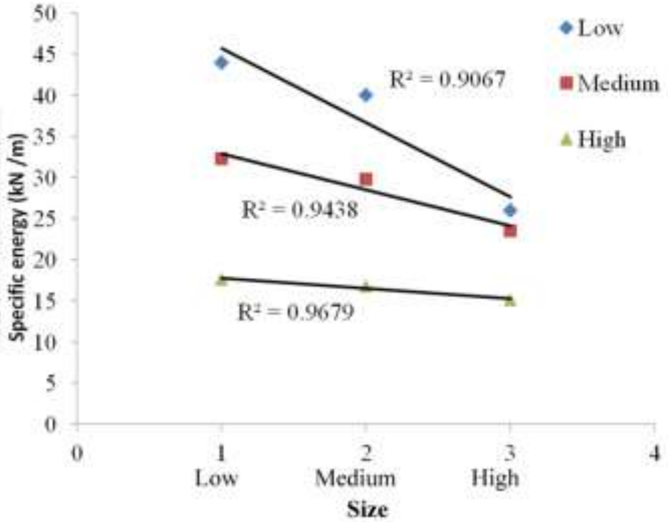


Fig. 8. Effect of moisture content and size of sugarcane stalks on the specific energy

Conclusion

The effects of the moisture content of cutting samples and the size of material on ultimate stresses and specific energies involved in the mechanical cutting of sugarcane stalks in linear cutting knife were determined. The low level moisture content of cane stalks for peak force and energy consumed low level of force and energy whereas for ultimate stress and specific energy a high level of energy was consumed. Going from high level to low level of moisture content a decrease in the amount of energy occurred for the mechanical cutting process. Also both ultimate stress and specific shearing energy decreased with an increase in size of cutting section in sugarcane stalks. Therefore, cutting the high level of moisture content cane stalks in large size is better than cutting the low level of moisture content cane stalks in small size for reducing the consumed energy for mechanical cutting process. This paper concludes with information on engineering properties of sugarcane stalks which may be useful for designing the equipment used for harvesting, threshing, and processing. It is recommended that other engineering properties such as coefficient of friction, bulk density, tensile strength, rigidity modulus, and Poisson’s ratio be measured or calculated to provide fairly comprehensive information on design parameters involved in sugarcane harvesting and processing.

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