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Shearing characteristics of sugar cane (*Saccharum officinarum* L.) stalks as a function of the rate of the applied force

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Abstract

This research was carried out to determine the effect of loading rate and internode position on shearing characteristics of sugar cane stalk. The experiments were conducted at three loading rates of 5, 10, and 15 mm min^{-1} and at ten internode positions down from the flower. Based on the result obtained, loading rate had significant effect on the shear strength and specific shearing energy of the stalk. With increasing loading rate, the shear strength and specific shearing energy increased. Therefore, lower rates of blades are recommended for reducing energy requirement during harvesting and processing sugar cane stalks. In addition, the internode position had a significant effect on the specific shearing energy, while it did not have significant effect on the shear strength. The specific shearing energy increased towards the lower internodes. The average shear strength was obtained as 3.64 MPa varying from 3.03 to 4.43 MPa. The average specific shearing energy was calculated as 51.41 mJ mm^{-2} ranging from 37.42 to 64.25 mJ mm^{-2}. The results of this study are useful for designing and optimizing equipment associated with harvesting, threshing, and processing

Keywords: Sugar cane; Internode position; Shear strength; Specific shearing energy

Abbreviations:

A	cross-section area, mm^2
d	diameter of stalk, mm
E_s	shearing energy, mJ
E_{sc}	specific shearing energy, mJ mm^{-2}
F_s	shear force, N
L	stalk length, mm
τ_s	shear strength, MPa

Introduction

Sugar cane, a member of the grass family, is a perennial 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 60378 ha with an annual production of about 3034936 ton (FAO, 2009). The mechanical properties of Sugar cane stalk are essential for the design of equipment and the analysis of the behavior of the product during agricultural process operations such as harvesting, handling, threshing, and processing. Most studies on the mechanical properties of plants have been carried out during their growth using failure criteria (force, stress and energy) or their Young's modulus and the modulus of rigidity. Studies have focused on plant anatomy, lodging processes, harvest optimisation, animal nutrition, industrial applications and the decomposition of wheat straw in soil (McNulty and Mohsenin, 1979; Annoussamy et al., 2000). The properties of the cellular material that are important in cutting are compression, tension, bending, shearing, density and friction. 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 at different heights of the plant stalk (İnce et al., 2005). Methods and procedures for determining most mechanical and rheological properties of agricultural products have been described by Mohsenin (1986). Several studies have been conducted to determine mechanical properties of plants. Dernedde (1970) used a shear box method to measure shear strength of different varieties of forage materials tested individually. Shear strength ranges of 25–88 MPa and 59–128 MPa were reported for two sets of data, with maxima at moisture contents of 20% w.b. and 35% w.b., respectively. The form of the curves relating shear strength to moisture content was analogous to those found by Liljedhal et al. (1961) who investigated the specific energy required to cut beds of

Table 1. Physical properties of sugar cane stalk internodes.

Internode	IN1*	IN2	IN3	IN4	IN5	IN6	IN7	IN8	IN9	IN10
N	15	15	15	15	15	15	15	15	15	15
d (mm)	23.71_{a}	24.25_{a}	24.01_{a}	24.16_{a}	24.06_{a}	24.08_{a}	23.89_{a}	23.98_{a}	23.42_{a}	23.49_{a}
A (mm^2)	447.02_{a}	464.78_{a}	457.53_{a}	463.12_{a}	459.12_{a}	459.16_{a}	452.49_{a}	454.89_{a}	434.58_{a}	437.37_{a}
L (mm)	85.24_{de}	84.60_{e}	93.20_{cde}	97.20_{bcd}	101.13_{abc}	105.20_{abc}	109.13_{ab}	112.66_{a}	110.66_{a}	104.13_{abc}

*IN1, IN2 … and IN10: first, second … and tenth internodes, respectively; N: number of observations; d: diameter of stalk; A: cross–section area; L: length; a-e: means followed by different letters are significantly different from others in the same line (P<0.05).

Table 2. Mean comparison of shear strength and specific shearing energy of sugar cane stalk in different loading rates and internode positions

Loading rate (mm min^{-2})*	Shear strength (MPa)	Specific shearing energy (mJ mm^{-2})
5	3.47_{b}	48.32_{b}
10	3.65_{ab}	50.91_{ab}
15	3.81_{a}	55.01_{a}
Internode position		
IN1	3.58_{a}	48.21_{ab}
IN2	3.61_{a}	46.73_{b}
IN3	3.91_{a}	51.80_{ab}
IN4	3.62_{a}	50.77_{ab}
IN5	3.38_{a}	50.86_{ab}
IN6	3.45_{a}	48.93_{ab}
IN7	3.56_{a}	51.33_{ab}
IN8	3.42_{a}	50.36_{ab}
IN9	3.92_{a}	56.61_{ab}
IN10	3.97_{a}	58.52_{a}

*The means with minimum common letter are not significantly different (*P*>0.05) according to Duncan's multiple ranges test; IN1, IN2 … and IN10: first, second … and tenth internodes, respectively.

Table 3. Shearing characteristics of sugar cane stalk at different loading rates and internode positions

Loading rate (mm min^{-1})	Internode*									
	Shear strength (MPa)									
	IN1	IN2	IN3	IN4	IN5	IN6	IN7	IN8	IN9	IN10
5	3.03_{d}	3.32_{abcd}	3.55_{abcd}	3.67_{abcd}	3.19_{bcd}	3.04_{d}	3.54_{abcd}	3.51_{abcd}	3.93_{abcd}	3.88_{abcd}
10	4.33_{abc}	4.05_{abcd}	4.31_{abc}	3.78_{abcd}	3.37_{abcd}	3.16_{cd}	3.27_{abcd}	3.16_{cd}	3.38_{abcd}	3.66_{abcd}
15	3.39_{abcd}	3.46_{abcd}	3.86_{abcd}	3.42_{abcd}	3.58_{abcd}	4.15_{abcd}	3.87_{abcd}	3.59_{abcd}	4.43_{a}	4.37_{ab}
	Specific shearing energy (mJ mm^{-2})									
5	37.42_{c}	41.69_{bc}	46.19_{abc}	51.22_{abc}	45.14_{abc}	44.32_{abc}	51.66_{abc}	50.36_{abc}	59.66_{ab}	55.54_{abc}
10	58.43_{ab}	52.35_{abc}	56.10_{abc}	53.18_{abc}	49.88_{abc}	41.35_{bc}	48.25_{abc}	45.33_{abc}	48.43_{abc}	55.75_{abc}
15	48.79_{abc}	46.16_{abc}	53.11_{abc}	47.91_{abc}	57.57_{abc}	61.14_{ab}	54.07_{abc}	55.39_{abc}	61.74_{ab}	64.25_{a}

*IN1, IN2 … and IN10: first, second … and tenth internodes, respectively; a-d: means followed by different letters are significantly different from others in the same line (P<0.05).

forage. O'Dogherty et al. (1989) measured the shear strength of six varieties of wheat straw. They found that the mean ultimate shear strength was in the range of 5.39 to 6.98 MPa for five varieties of winter wheat and was equal to 8.53 MPa for a spring wheat (var. Alexander) having moisture contents ranging from 10 to 15% w.b. Kushaha et al. (1983) reported mean values of shear strength of wheat straw in the range of 7–22 MPa with some dependence on moisture content. 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 1/10 the energy to shear alfalfa transversely. McRandal and McNulty (1980) conducted shearing experiments on field grasses and found that the mean shearing stress was 16 MPa and the mean specific 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 force required to cut stretched (bent) stalks was 50% less than that for straight stalks. Several studies have been conducted in recent years to determine mechanical properties of plants such as: Chen et al. (2004) on hemp stems, İnce et al. (2005) on sunflower stalks, Nazari Galedar et al. (2008) on alfalfa stems, Tavakoli et al. (2009b) on barely straw, Tavakoli et al. (2009a) on wheat straw, Zareiforoush et al. (2010) on rice straw, and Mahmoodi and Jafari (2010) on cumin stem. There is no published work relating to the effect of the rate of the applied force on shearing characteristics of sugar cane stalk. Therefore, the objective of this study is to determine the effect of loading rate on shearing characteristics, namely, shear strength and specific shearing energy, of sugar cane stalk.

Materials and methods

This study was carried out at the Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering

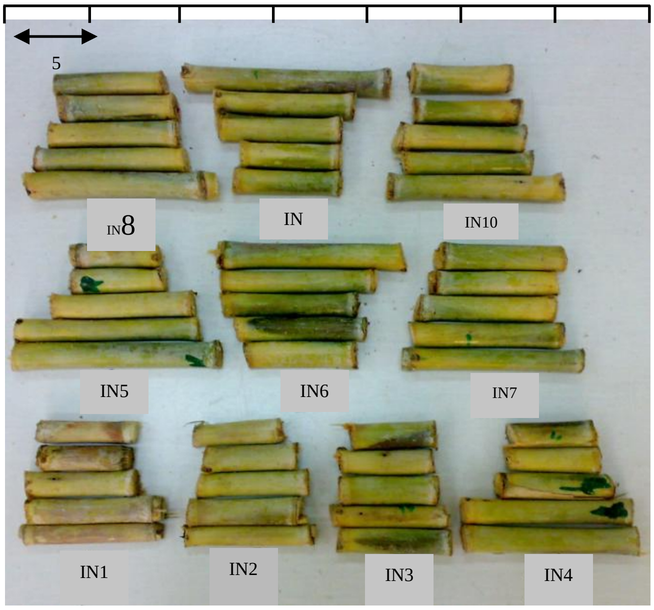

Fig 1. Sugar cane stalk internodes; IN1, IN2 … and IN10: The first, second … and tenth internodes, respectively.

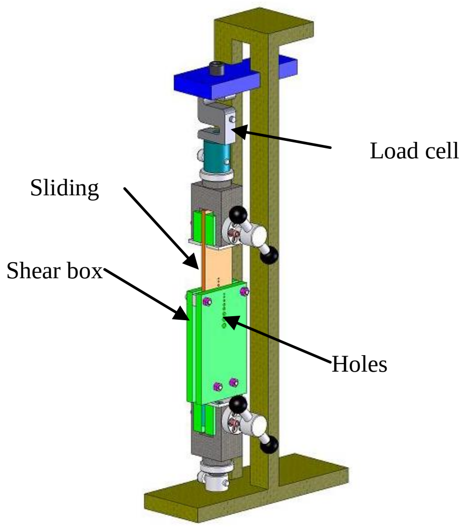

Fig 2. Apparatus used to measure shearing characteristics of sugar cane stalk internodes (the stalk specimens are placed into the holes and loaded by the sliding plate, the applied force is measured by the load cell sensor)

and Technology, University of Tehran, Karaj, Iran, in August 2010. The sugar cane stalks (IRC99-01 variety) used for the present study were from the prevalent varieties of sugar cane in Iran and were obtained from the agronomy farm of the agro-industry of Mirza Kouchak Khan, Ahvaz, Iran, in August 2010. The stalks were collected at harvesting time and their internodes were separated according to their position down from the flower (Fig. 1). Leaf blades and sheaths were removed prior to any treatment or measurement (Annoussamy et al., 2000). To determine the average moisture content of the stalks, the specimens were weighed and oven-dried at 103°C for 72 h and then weighed. The average moisture content of the specimens was 75.27% wet basis. Ten internodes of the sugar cane stalk, namely, IN1, IN2, IN3, IN4, IN5, IN6, IN7, IN8, IN9 and IN10, were studied in this study (Fig. 1). Each internode was described by measuring its length (to the nearest 1 mm) and its diameter (to the nearest 1 μm) using a digital caliper (Mitutoyo, Japan).

Experimental procedure

The shearing characteristics of sugar cane stalk were assessed using a shearing test similar to those described by İnce et al. (2005), Nazari Galedar et al. (2008), Tavakoli et al. (2009b) and Zareiforoush et al. (2010) (Fig. 2). All measurements were made using a proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Tehran, Iran, 2007).

Shearing test

The shear strength was measured in double shear using a shear box (Fig. 2) consisting essentially of two fixed parallel hardened steel plates 6 mm apart, between which a third plate can slide freely in a close sliding fit. A series of holes with different diameters ranging from 10 to 30 mm were drilled through the plates to accommodate internodes of differing diameters. Shear force was applied to the stalk specimens by mounting the shear box in the tension/compression testing machine. The sliding plate was loaded at three loading rates of 5, 10 and 15 mm min^{-1} and, as for the shear test, the applied force was measured by a strain-gauge load cell and a force-time record obtained up to the specimen failure. The shear failure stress (or ultimate shear strength), τ_s, of the specimen was calculated from the following equation (Tavakoli et al., 2009b; Zareiforoush et al., 2010):

$$\tau_s = \frac{F_s}{2A} \qquad (1)$$

where: τ_s is the shear strength (MPa), F_s is the shear force at failure (N) and A is the wall area of the specimen at the failure cross-section (mm^2). The shearing energy, E_s, was calculated by integrating the area under curves of shear force and displacement (Chen et al., 2004; Nazari Galedar et al., 2008; Zareiforoush et al., 2010) using a standard computer program (ver. 5, SMT Machine Linker, SANTAM Company, Tehran, Iran, 2007). An example of the shear force versus displacement curves is shown in Fig. 3. The curves were used to evaluate: a) the shear strength, obtained by using the maximum recorded force; b) the shearing energy, given by the area under the curves. The specific shearing energy, Esc was calculated by:

$$E_{sc} = \frac{E_s}{A} \qquad (2)$$

where: E_{sc} is the specific shearing energy (mJ mm^{-2}) and E_s is the shearing energy (mJ).

Experimental design and statistical analysis

This study was planned as a completely randomized block design. The shearing characteristics were determined with five replications in each treatment. Experimental data were analysed using analysis of variance (ANOVA) and the means were compared at the 1% and 5% levels of significance using the Duncan's multiple range tests in SPSS software (ver. 15, SPSS, Inc., Chicago, IL, USA, 2008).

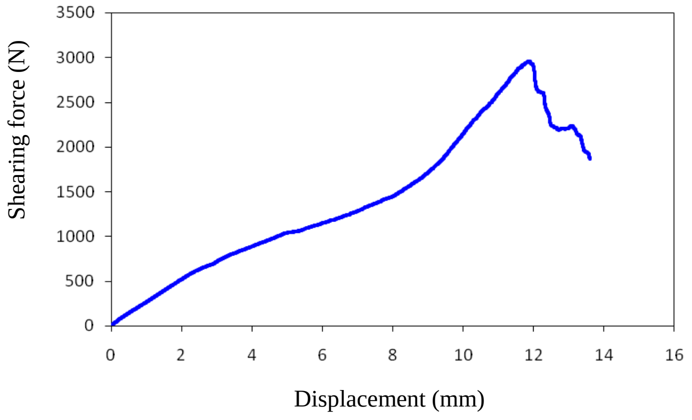

Fig 3. The shearing force versus displacement curve for sugar cane stalk.

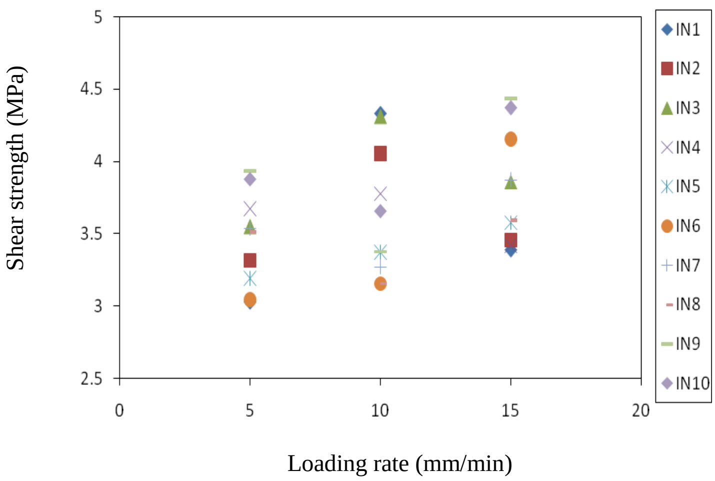

Fig 4. Effect of loading rate and internode position on shear strength of sugar cane stalk.

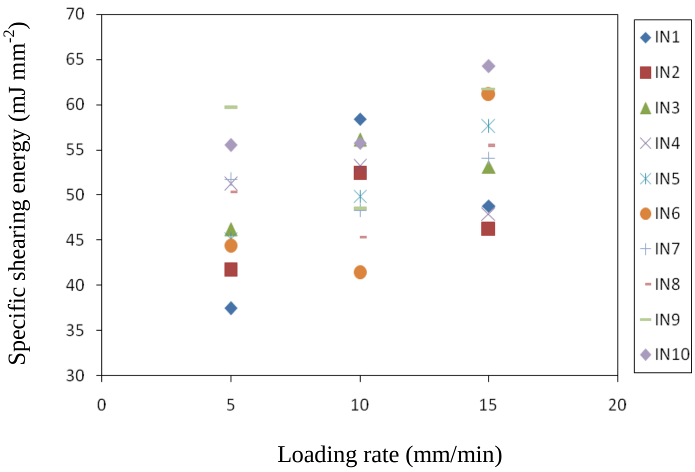

Fig 5. Effect of loading rate and internode position on specific shearing energy of sugar cane stalk.

Results and discussion

The variance analysis of the data indicated that the effect of loading rate on the shear strength and specific shearing energy was significant at 5% probability level. In addition, internode position created a significant effect ($P<0.05$) on the specific shearing energy, while it did not have significant effect ($P>0.05$) on the shear strength. Based on the statistical analysis, the interaction effect of loading rate × internode on the shear strength and specific shearing energy was not significant ($P>0.05$). The results obtained are discussed in details as follows.

Physical properties

The mean values for the physical properties of sugar cane stalk are presented in Table 1. By Duncan's multiple range tests, the effect of internode position on the stalk's length was significant at 1% probability level, while the effect on the stalk's diameter and cross-sectional area was not significant ($P>0.05$). The average diameter and cross-sectional area of the stalk were 23.90 mm and 453.01 mm^2, respectively. The average stalk's length was obtained as 100.31 mm varying from 84.60 to 112.66 mm.

Shear strength

The mean values of the shear strength at different loading rates and internodes are presented in Table 2. According to the Duncan's multiple range tests, the loading rate had significant effect ($P<0.05$) on the shear strength, while internode position did not have significant effect ($P>0.05$) on the characteristic. The shear strength increased with increasing loading rate (Table 2). The average shear strength was obtained as 3.64 MPa varying from 3.03 to 4.43 MPa. Kushaha et al. (1983) reported mean values of shear strength of wheat straw in the range of 7–22 MPa for stem moisture content ranging from 5 to 30% w.b. The effect of moisture content and level of crop on the shear strength of alfalfa stems was studied by Nazari Galedar et al. (2008). They reported that the shear strength of alfalfa stems increased from 5.98 to 28.16 MPa at the upper level with the lowest moisture content (10% w.b.) and the lower level with the highest moisture content (80% w.b.), respectively. Tavakoli et al. (2009b) determined shear strength of barley straw. They reported that the values of the shear strength were within the ranges 3.90–5.27 MPa, 4.31–5.96 MPa, and 4.49–6.18 MPa for the first, second and third internode positions, respectively. Tavakoli et al. (2009a) showed that the shear strength of wheat straw increased towards the third internode position. Zareiforoush et al. (2010) investigated the effect of loading rate and internode position on the shearing characteristics of rice straw. They showed that the loading rate did not have significant effect ($P>0.05$) on the shear strength of rice straw, while the shear strength increased towards the upper internodes. They reported the average shear strength of rice straw as 12.18 MPa which varied from 8.45 to 20.22 MPa. The interaction effect of loading rate × internode position on the shear strength of sugar cane stalk is shown in Fig. 4 and Table 3.

Specific shearing energy

The mean values of the specific shearing energy at different loading rates and internodes are presented in Table 2. According to the Duncan's multiple range tests, the loading rate and internode position created a significant effect ($P<0.05$) on the specific shearing energy. The specific shearing energy increased with increasing loading rate and towards the lower internodes (Table 2). The specific shearing energy was higher in the lower internodes, possibly due to the accumulation of more mature fibres in the stem. Similar results for effects of loading rate and internode position on shearing energy were reported by Zareiforoush et al. (2010) for rice straw. The average specific shearing energy was calculated as 51.41 mJ mm^{-2} ranging from 37.42 to 64.25 mJ mm^{-2}. Based on the reports of McRandal and McNulty (1980) in the case of field grasses, the mean specific shearing energy was 12.0 mJ mm^{-2}. The specific shearing energy of sunflower stalks was determined by İnce et al. (2005), who reported the range of 1.99 to 10.08 mJ mm^{-2} for moisture content range of 20 to 80% d.b. Nazari Galedar et al. (2008) reported that the values of the shearing energy of alfalfa stem varied from 20.2–73.1 mJ, 64.20–187.60 mJ, and 185.20–345.8 mJ for the upper, middle and lower levels, respectively, at the different moisture contents (in the range of 10 to 80% w.b.). Tavakoli et al. (2009b) showed that the values of specific shearing energy of barely straw varied from 18.79 to 32.53 mJ mm^{-2}. The values obtained in the current study for the sugar cane stalk were higher than those of field grasses, sunflower stalks, and barley straw indicating higher shearing resistance of sugar cane stalk. The interaction effect of loading rate × internode position on the specific shearing energy of sugar cane stalk is shown in Fig. 5 and Table 3.

Conclusions

The following conclusions were drawn from the investigation of the effect of loading rate and internode position on the shear strength and specific shearing energy of sugar cane stalk. The loading rate had significant effect ($P<0.05$) on the shear strength and specific shearing. Both the characteristics increased with increasing loading rate. Therefore, lower rates of blades are recommended for reducing energy requirement during harvesting and processing sugar cane stalks. The internode position had significant effect ($P<0.05$) on the specific shearing energy, while it did not have significant effect on the shear strength ($P>0.05$). The specific shearing energy increased towards the lower internodes. The mean values of the shear strength and specific shearing energy were obtained as 3.64 MPa and 51.41 mJ mm^{-2}, respectively. This paper concludes with information on the engineering properties of sugar cane stalk which may be useful for designing the equipment used for harvesting, threshing, and processing. It is recommended that other engineering properties such as bending strength, Young’s modulus, 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 rice straw harvesting and processing equipment.

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