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Full Length Research Paper

Comparison of mechanical properties of wheat and rice straw influenced by loading rates

Farman Ali Chandio[1, 2], Ji Changying[1]*, Ahmed Ali Tagar[1], Irshad Ali Mari[1], T. Guangzhao[1] and Do Minh Cuong[1]

[1]Department of Agricultural Mechanization, College of Engineering, Nanjing Agricultural University, Post Code 210031, Nanjing, Peoples Republic of China.
[2]Department of Farm Power and Machinery, Faculty of Agricultural Engineering, Sindh Agriculture University, Tandojam, Pakistan.

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This study investigates the comparison of mechanical properties of wheat and rice straw such as shear strength, specific shearing energy and cutting forces. The experiments were conducted at three loading rate of 15, 20 and 25 mm min^{-1} and three internode positions 70 (N1), 130 (N2) and 190 (N3) mm down from the ear. Results show that by increasing the loading rate, strength of wheat and rice straw changed from 8.12 to 22.94 and 6.06 to 14.33 MPa and specific shear energy was varied from 12.10 to 18.64 and 10.40 to 16.17 mJ mm^{-2}, respectively. Moreover, the values of cutting forces of wheat and rice straw were within the ranges 13.23 to 19.50 and 9.40 to 16.70 N. Whereas the shear strength, specific shearing energy and cutting force were higher at higher loading rate at the third internode of both straw internode positions. The shear strength, specific shearing energy and cutting force of rice straw were significantly higher (p<0.05) than that of wheat straw. With respect to the findings of the present research study, it is concluded that with decreasing loading rate of cutting blade toward the first internode, more energy can be saved by harvesting and threshing machines.

Key words: Cutting force, rice straw, shear strength, specific shearing energy, wheat straw.

INTRODUCTION

Rice and wheat are the two largest cereal food crops of China and their total production accounts for 70% of the total grain production. In the middle and lower reaches of the Yangtze River, the annual double cropping of rice and wheat accounts for more than 8×10^6 ha (Wang, 2005). Increasing interest in mechanized rice and wheat harvesting and commercial use of rice and wheat straw have prompted the need for engineering data on stem properties (Yore et al., 2002). The variations in the physical properties of plant straws and the resistance of cutting equipment have to be known in order to understand the behavior of material. From several years, farmers have been using straw (rice and wheat) incorporated into the plowed layer, mulch to improve the soil stability, organic matter and maintain the temperature and moisture content in the field condition.

The mechanical properties of rice and wheat straw 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 optimization, animal nutrition, industrial applications and the decomposition of wheat straw in soil (McNulty and Mohsenin, 1979; Annoussamy et al., 2000). The important

*Corresponding author. E-mail: chyji@njau.edu.cn.

Abbreviations: WS, Wheat straw; **RS,** rice straw.

Table 1. Physical properties of WS and RS at different internodes position.

Parameter	WS			RS		
	N1	N2	N3	N1	N2	N3
Thickness	0.473[b]	0.433[c]	0.543[b]	0.503[a]	0.476[b]	0.395[c]
Diameter	3.33[b]	3.87[a]	3.90[a]	3.96[c]	4.21[b]	4.31[a]
X-sectional area	8.70[c]	11.75[b]	11.93[a]	12.31[c]	13.91[b]	14.58[a]
Length	70[c]	130[b]	190[a]	70[c]	130[b]	190[a]

*N1, N2 and N3, First, second and third internode position, respectively. [a-c]Resources followed by superscript letters in a column are significantly different from others in the same column (P<0.05).

properties of cellular material are: cutting compression, tension, bending, shearing, and friction etc. These properties depend on the species, variety, stalk diameter, maturity, moisture content and structure (Bright and Kleis, 1964; Persson, 1987). Several studies have been conducted to determine mechanical properties of plants. The curves relating shear strength to moisture content were analogous to those found by Liljedhal et al. (1961) who investigated the specific energy required to cut beds of forage. O' Dogherty et al. (1989) measured the shear strength of six varieties of wheat straw.

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 to 5.27 MPa, 4.31 to 5.96 MPa and 4.49 to 6.18 MPa for the first, second and third internode positions, respectively. Even today no such work has been done on comparison of mechanical properties of the wheat and rice straw. Therefore, this study was conducted to compare the mechanical properties of wheat and rice straw such as shear strength, specific shearing energy and cutting force at different loading rates.

MATERIALS AND METHODS

Rice (Wu yungen rice 23) and wheat (Nanjing wheat 13) straw were collected at harvesting time from Jiangpu experimental farm of Nanjing Agricultural University, Jiangsu Province of China which is located at latitude of 32° 3' 4.96'' N and longitude of 118° 36' 38.78'' W). The experiment was conducted at Agricultural material characteristics research laboratory, College of Engineering, Nanjing Agricultural University, Nanjing, China during the year 2011.

Straw internode preparation

The wheat straw (WS) and rice straw (RS) were chopped manually into three lengths (70, 130 and 190 mm) and were labeled as N1, N2, and N3, respectively. Leaf blades and sheaths were removed prior to measurement (Annoussamy et al., 2000) (Table 1).

Experimental method

In order to determine the average moisture content of WS and RS, six samples of 30 g were weighed and dried in an oven of 105°C for 24 h and then reweighed (ASAE, 2006). Straw moisture content was calculated by the given formula:

$$M.C = \frac{W_{wt} - W_{dt}}{W_{dt} - W_t} \times 100 \quad (1)$$

Where, M.C = moisture content, %; W_{wt} = weight of the moisture of straw with tare, g; W_{dt} = weight of the dried straw with tare, g; W_t = weight of the container, g.

Average moisture content of the WS and RS were 18.10%, respectively. The straw internodes were separated out according to their position down from the ear (Annoussamy et al., 2000). In each internode position, internode length, thickness, diameters were measured using a digital caliper (Vernier caliper, China) with the accuracy of 0.01 mm (Figure 1).

Fabrication of shear box

The shear box was fabricated with steel sheets of 130 × 90 × 25 mm dimensions having 5 mm thickness. Six holes of 2 to 7 mm were drilled into side plates of box to provide the passage of straw internode from one plate to another plate. A sliding plate was also fabricated to deflect the straw internode at the center. The shear box was then attached to compression testing machine through wedge grip at bottom and sliding plate at upper side as shown in Figure 2.

Testing procedure

The mechanical properties of WS and RS were measured using a shearing test similar to those described by O'Dogherty et al. (1995), İnce et al. (2005); Nazari Galedar et al. (2008), Crook and Ennos (1994), Annoussamy et al. (2000), Nazari Galedar et al. (2008), Tavakoli et al. (2009b) and Zareiforoush et al. (2010).

Shearing test

The shear box (Figure 1) was attached with mounted in compressive testing machine. The sliding plate was loaded at three loading rates of 15, 20 and 25 mm min^{-1}. To determine shear test, the applied force was measured by S-type load cell and a force-time was recorded up to the specimen failure of straw. The shear failure stress (ultimate shear strength) of the specimen was calculated from the equation below (Tavakoli et al., 2008; Tavakoli et al., 2009b; Zareiforoush et al., 2010).

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

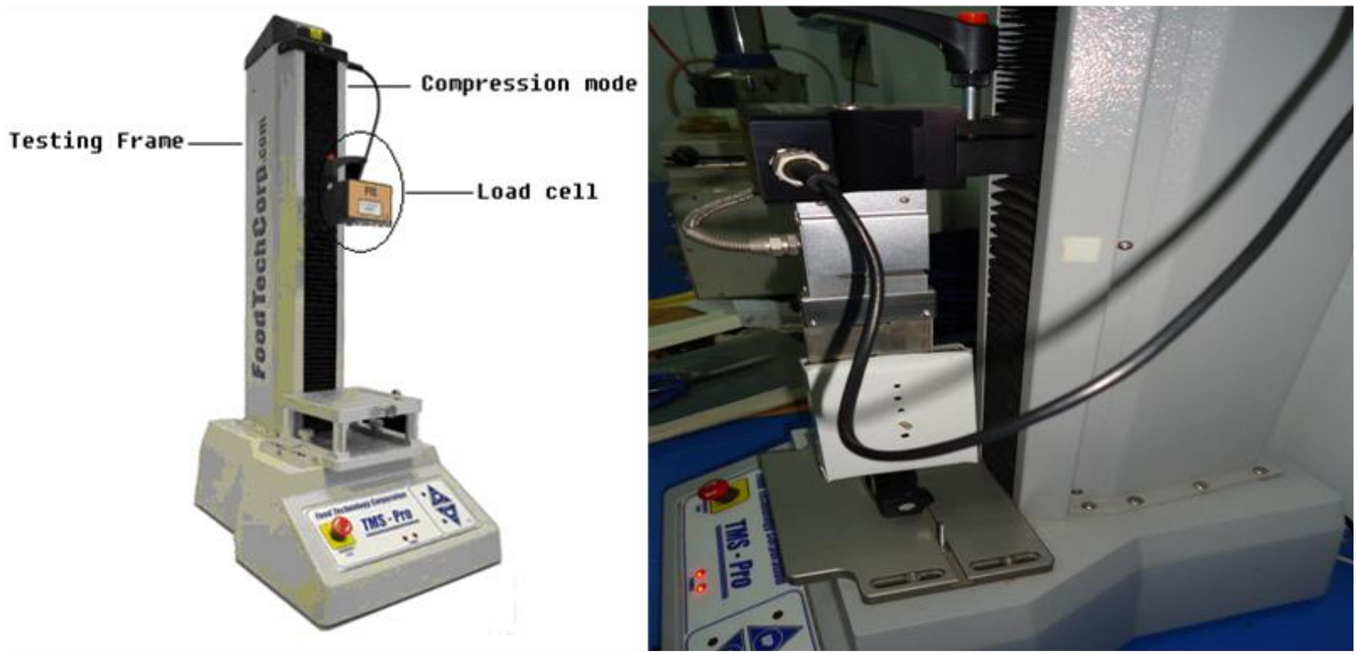

Figure 1. A TMS-Pro texture analyzer testing machine used to measure the shear strength and cutting force of WS and RS.

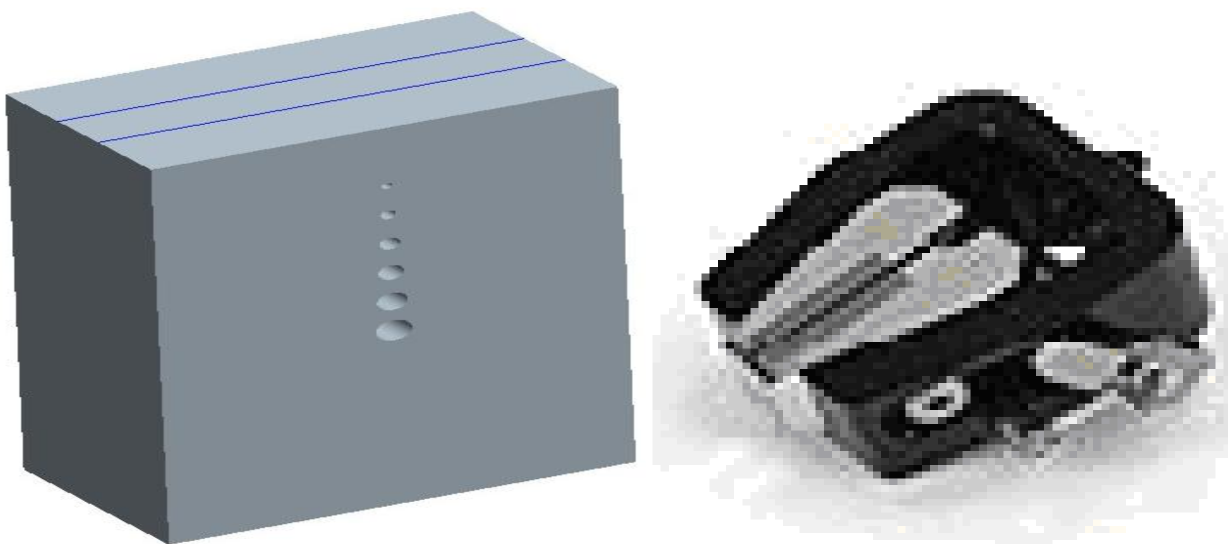

Figure 2. Shear box and wedge grip.

Where, τ_s = shear strength, MPa; *F*s = shear force at failure, N; *A* = wall area of the specimen at the failure cross-section, mm^2 (Table 2).

The shearing energy was calculated by integrating the area under curves of shear force and displacement (Chattopadhyay and Pandey, 1999; Chen et al., 2004; Nazari Galedar et al., 2008; Zareiforoush et al., 2010) using a lab texture pro computer program for data acquisition (TMS-Pro computer-controlled texture measurement system). The specific shearing energy, *Esc* was was calculated by given formula:

$$Esc = \frac{Es}{A} \qquad (3)$$

Where, *Es* = shearing energy mm^2 (Table 3).

Cutting test

WS and RS were tested by shear test apparatus under Warner-Bratzler blade at straw length 70,130 and 190 mm. The test set comprises of a blade holder with two locking screws. A central slot

Table 2. Comparison of shear strength of WS and RS at different loading rates and internode positions.

Loading rate	Shear strength (MPa)					
	WS			RS		
	N1	N2	N3	N1	N2	N3
15	8.12^{c}	14.01^{b}	20.42^{a}	6.06^{c}	7.12^{c}	8.12^{a}
20	11.08^{c}	17.83^{b}	22.46^{a}	7.99^{c}	9.79^{c}	10.23^{c}
25	12.78^{c}	16.87^{b}	22.94^{a}	10.44^{bc}	10.33^{c}	14.33^{c}

Table 3. Comparison of specific shearing energy of WS and RS at different loading rates and internode position.

Loading rate	Specific shearing energy (mJ mm^{-2})					
	WS			RS		
	N1	N2	N3	N1	N2	N3
15	12.1^{b}	14.07^{a}	17.21^{c}	10.40^{c}	12.32^{a}	13.32^{b}
20	12.83^{a}	16.51^{b}	18.64^{c}	11.44^{b}	13.17^{a}	16.17^{c}
25	13.50^{b}	15.23^{a}	18.40^{a}	10.68^{c}	11.86^{b}	16.12^{c}

***Means with different superscript letters in a column are significantly different ($P<0.05$) according to Duncan's multiple ranges test. N1, N2 and N3, First, second and third internode position, respectively.

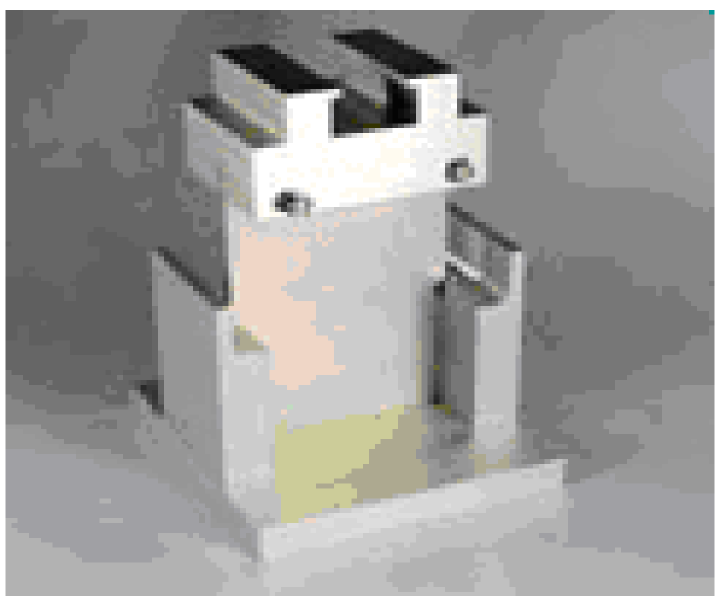

Figure 3. Warner-Bratzler Blade for cutting test.

allows free movement of the blade to limit friction during analysis (Figure 3).

Statistical analysis

This research study was planned as a completely randomized block design (RCBD) with five replications. One way of variance (ANOVA) and Duncan's multiple range tests (DRMT) were carried out to assess significant differences between means ($p<0.05$) using SPSS (ver. 16, SPSS, Inc., Chicago, IL, USA).

RESULTS AND DISCUSSION

The variance analysis of the data indicated that the effect of loading rate on the shear strength, specific shearing energy and cutting force of RS were significantly higher ($p<0.05$) than that WS. Duncan test showed that there were significant differences among the three loading rates ($p<0.05$) on shear strength, young's specific shearing energy and cutting force. The results are widely discussed as follows:

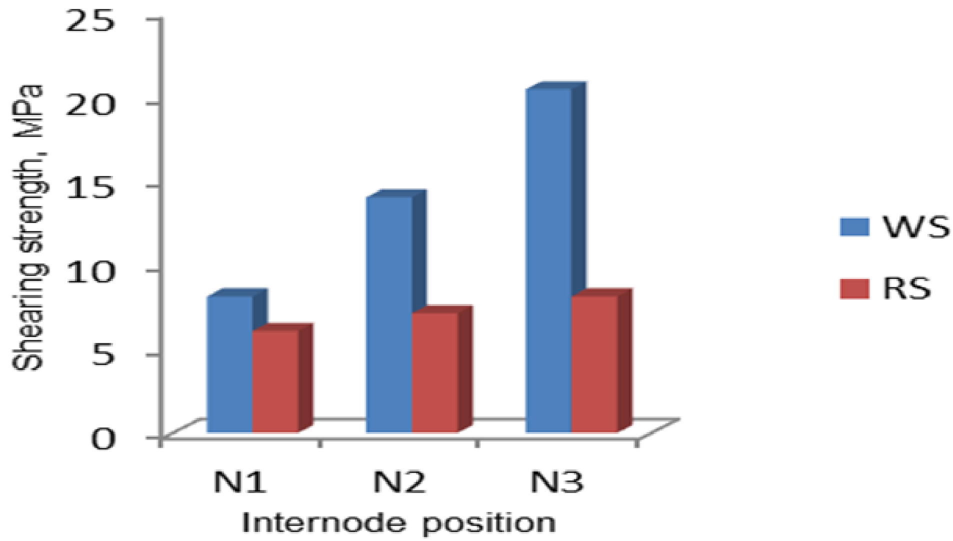

Figure 4. Shear strength of WS and RS at different internode positions under 15 mm min^{-1}.

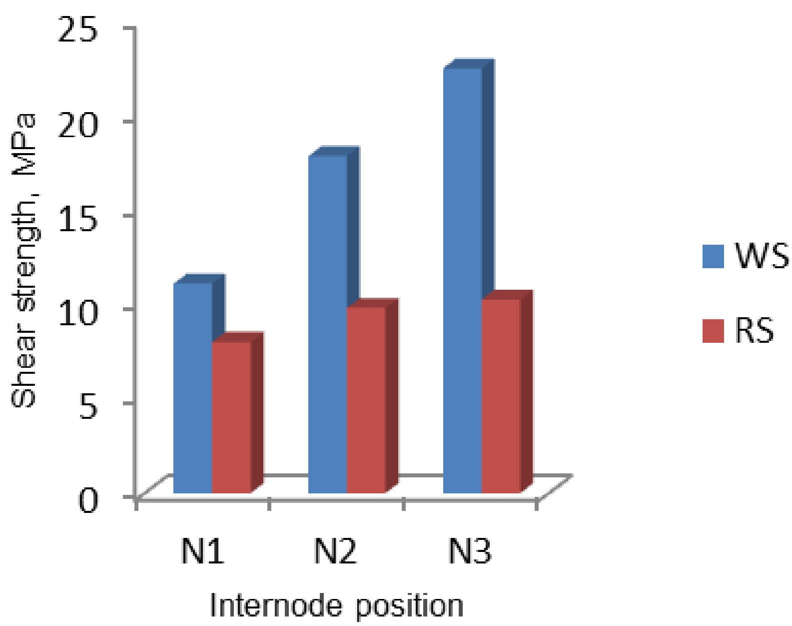

Figure 5. Shear strength of WS and RS at different internode positions under 20 mm min^{-1}.

Shear strength

The average values of shear strength for internodes (N1, N2 and N3) of WS and RS with three loading rates are presented in Figures 4 to 6. The results of Internodes N1, N2 and N3 of WS varied from 8.12 to 12.78, 14.01 to 17.83 and 20.42 to 22.94 MPa, respectively, while the RS varied from 6.06 to 10.44, 7.12 to 10.33 and 8.12 to 14.33 MPa at N1, N2 and N3, respectively. The higher values of the shear strength for WS in comparison with RS indicate that the WS is inflexible. The shear strength of RS was significantly higher ($p<0.05$) than that of WS at three loading rates. The shear strength for both WS and RS increased at N3. On comparison, results of WS were higher than RS at loading rate of 25 mm min^{-1}. The shear strength was highest (22.94 MPa) at N3 for WS and RS (14.33 MPa) and lowest N1 (8.12 MPa) for WS and RS (6.06 MPa) at loading rate of 15 mm min^{-1}. These results

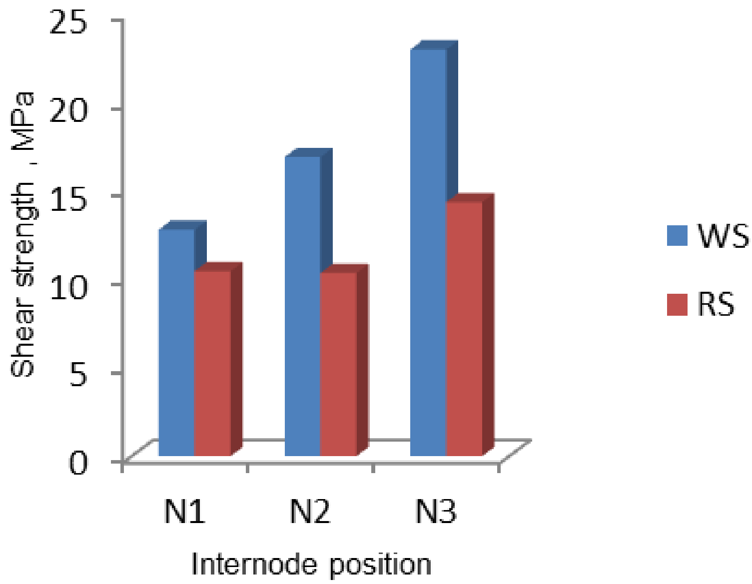

Figure 6. Shear strength of WS and RS at different internode positions under 25 mm min^{-1}.

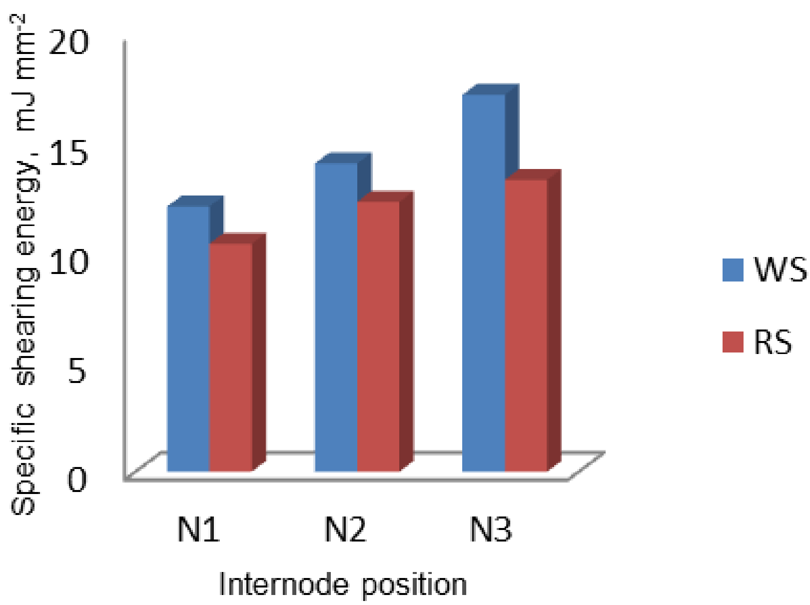

Figure 7. Influence of specific shearing energy of WS and RS at different internode position under 15 mm min^{-1}.

are in agreement with Tavakoli et al. (2009a) which showed that the shear strength of wheat straw increased towards the third internode position. These results are in agreement with Zareiforoush et al. (2010b) who concluded that the average shear strength was obtained as 12.18 MPa varying from 8.45 to 20.22 MPa at three loading rates: 5, 10 and 15 mm min^{-1}. Zareiforoush et al. (2010) investigated the effect of loading rate and internode position on the shearing characteristics of rice straw. They showed that the average shear strength was obtained as 12.18 MPa varying from 8.45 to 20.22 MPa. Tavakoli et al. (2009b) determined shear strength of barley straw. They reported that the values of the shear strength were within the ranges of 3.90 to 5.27, 4.31 to

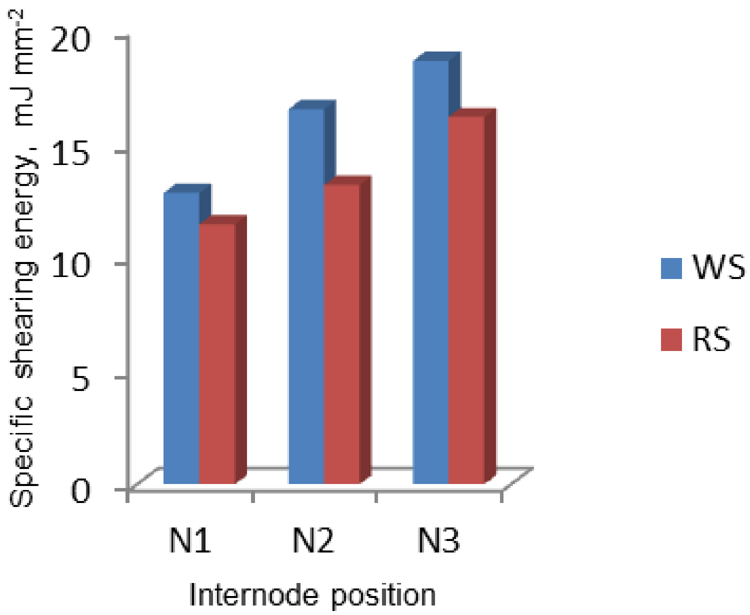

Figure 8. Influence of specific shearing energy of WS and RS at different internode position under 20 mm min^{-1}.

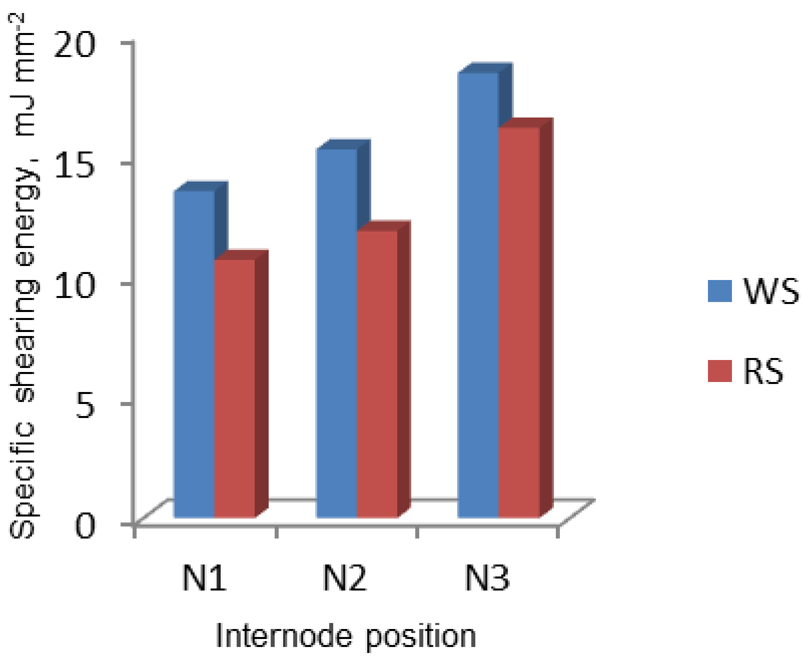

Figure 9. Influence of specific shearing energy of WS and RS at different internode position under 25 mm min^{-1}.

5.96, and 4.49 to 6.18 MPa for the first, second and third internode positions, respectively. Kushaha et al. (1983) reported mean values of shear strength of wheat straw in the range of 7 to 22 MPa for stem moisture content ranging from 5 to 30% w.b.

Specific shearing energy

The average values of specific shearing energy for internodes (N1, N2 and N3) of WS and RS with three loading rates are presented in Figures 7 to 9. The results

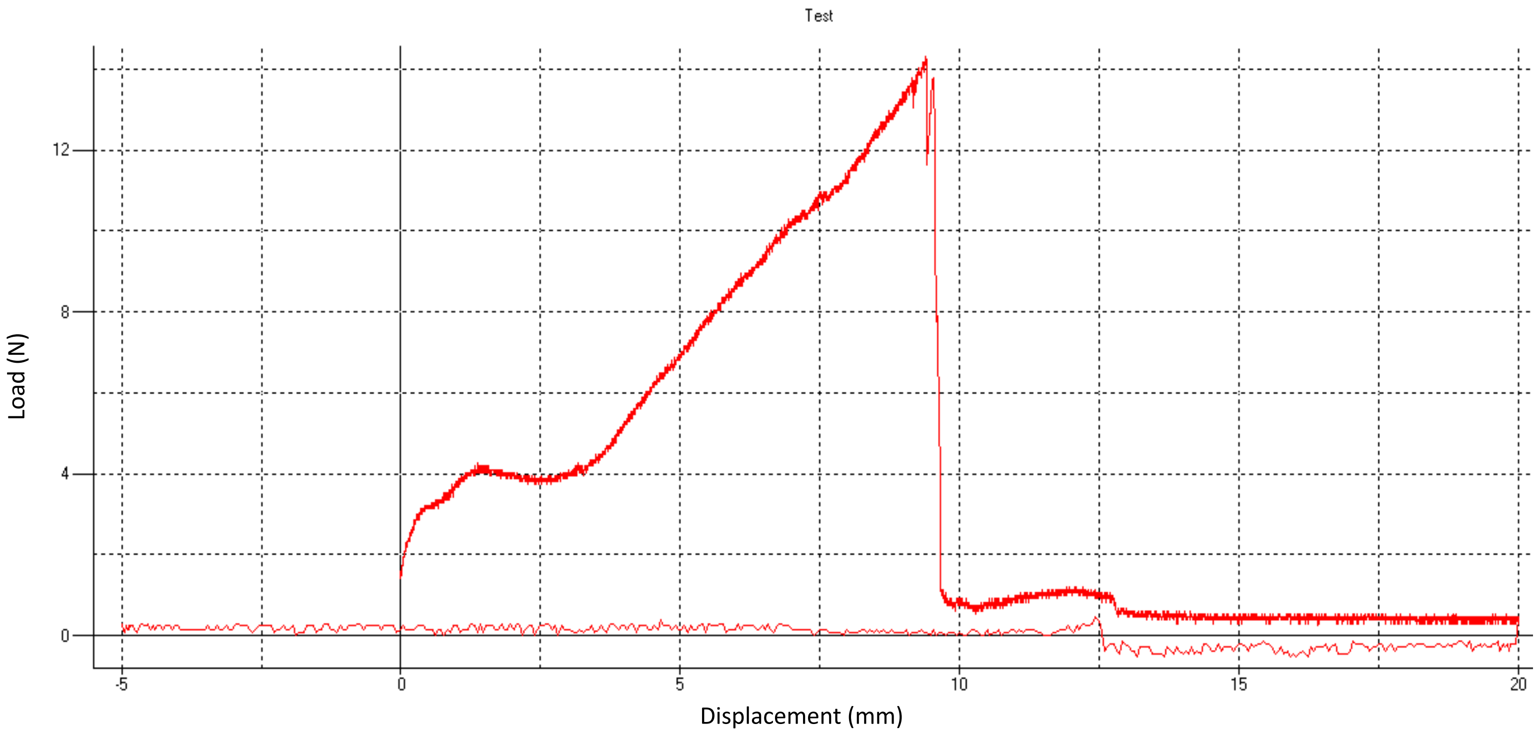

Figure 10. The cutting force versus displacement curve for WS.

of internodes N1, N2 and N3 of WS varied from 12.10 to 13.50, 14.07 to 16.51 and, 17.21 to 18.64 mJ mm^{-2}, respectively, while the RS varied from 10.40 to 11.44, 11.86 to 13.17 and 13.32 to 16.12 at N1, N2 and N3, respectively. According to the Duncan's multiple range tests, the values of the specific sharing energy for RS were significantly higher (p<0.01) than WS and Duncan test showed that there were significant differences among the three loading rates (P<0.05). This means that the energy requirement for shearing of WS is more than RS. The specific shearing energy was found highest at the position of WS at second internode on 20 mm min^{-1} while the lowest was found at RS at first internode position on 15 mm min^{-1}, so that overall, the specific energy was found lower at RS. Moreover, when the loading rate was increased from 15 to 25 mm min^{-1}, the specific shear energy decreased. The specific shear energy of both straw increased significantly (p<0.01) towards the third internode position. It was at maximum in the third internode position because of the accumulation of more mature straw (Figure 10). This effect of plant height on shearing energy requirement was also reported by Annoussamy et al. (2000) for wheat straw. Tavakoli et al. (2009b) showed that the values of specific shearing energy of wheat straw varied from 21.85 to 36.26 mJ mm^{-2}.

Cutting force

The average values of cutting force for internodes (N1, N2 and N3) of WS and RS with three loading rates are presented in Figure 11. The results of internodes N1, N2 and N3 of WS varied from 13.58 to 15.34, 13.23 to 16.41 and, 15.34 to 19.51 N, respectively, while the RS varied from 9.40 to

Table 4. Influence of cutting force of WS and RS at different internode position.

Loading rate	Cutting force, N					
	WS			RS		
	N1	N2	N3	N1	N2	N3
15	13.58[c]	13.23[b]	15.34[a]	9.40[c]	12.32[b]	14.12[a]
20	13.23[c]	14.51[a]	17.20[b]	12.32[c]	13.17[b]	13.86[a]
25	15,34[b]	16.41[b]	19.51[c]	14.12[c]	16.47[b]	16.70[a]

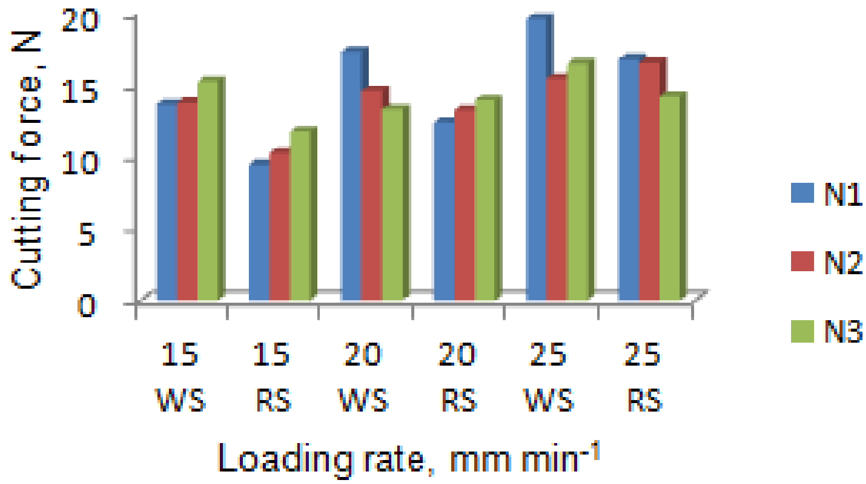

Figure 11. Influence of cutting force of WS and RS at different internode position under loading rates.

14.12, 12.32 to 16.47 and 14.12 to 16.70 N at N1, N2 and N3, respectively. The cutting force of WS and RS decreased towards the first internode position. With increase in loading rate of the blade, the cutting force decreased as reported by Annoussamy et al. (2000) for wheat straw and Nazari Galedar et al. (2008) for alfalfa stem. Khazaei et al. (2002) reported that by increasing the cutting speed from 20 to 500 mm min, the shearing strength and 1 there by, the shearing energy of pyrethrum flower stems decreased. According to the Duncan's multiple range tests, the effect of internode position on the cutting force of both straw was significant at the ($P>0.05$) significance level and RS had significantly higher ($P<0.05$) values than WS (Table 4).

Conclusions

Based on the results from this study, the following conclusions were drawn:

1) The shear strength and specific shear energy increased towards the third internode position at 25 mm min^{-2}, while a decrease was recorded at first internode position at 15 mm min^{-2} for both of WS and RS.
2) For all loading rates, the cutting force increased towards the third internode position of both WS and RS straw, while the cutting straw forces decreased at N1 and N2, respectively.
3) The shear strength, specific shearing energy and cutting forces of RS were significantly higher ($p<0.05$) than that WS.
4) New and innovative usage of wheat and rice straw will be greatly helpful to the designer of wheat and rice straw equipment, harvesting machines and tillage implements.
5) The results of present study indicate that threshing of wheat straw at lower loading rates can be recommended to minimize the shear strength and specific shearing energy requirements.

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