Effects of moisture content, internode position and loading rate on the bending characteristics of barley straw

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Abstract: This study was conducted with the aim to evaluate the effects of the moisture content, internode position, and loading rate on the bending characteristics of barley straw including bending stress and Young's modulus. In the study, 9 treatments were performed as randomised complete block design with 5 replications. The characteristics were determined at three moisture levels: 10%, 15%, and 20% wet basis, three loading rates: 5, 10, and 15 mm/min, and three internodes: the first, second, and third internodes. The results showed that both the bending stress and Young's modulus decreased with an increase in the moisture content and towards the third internode position. The average bending stress was obtained as 8.41 MPa varying from 6.32 to 12.41 MPa, while the average Young's modulus was calculated as 473.88 MPa ranging from 330.94 to 618.91 MPa. As shown by the results obtained, the values of the characteristics increased with increasing loading rate.

Keywords: barley; moisture content; loading rate; bending stress; Young's modulus

Barley (*Hordeum vulgare* L.) is a member of the grass family *Poaceae*. In Iran, barley is widely cultivated on approximately 1.8 million hectares with an annual production of 2.9×10^6 ton (FAO 2006). Several million tonnes of straw are produced from this crop annually. The straw usually serves as feed for animals and sometimes is incorporated into the plowed layer or used as mulch. For these purposes, straw must be processed after harvesting. For the selection of the design and operational parameters of the equipment used in harvesting, i.e. threshing, handling, and other barley straw processing, it is necessary to know its physical and mechanical properties.

Most studies on the mechanical properties of plants have been carried out during their growth using failure criteria (force, stress, and energy). The studies have focused on the plant anatomy, lodging processes, harvest optimisation, animal nutrition, industrial applications, and decomposition of wheat straw in soil (McNulty & Mohsenin 1979; Annoussamy *et al.* 2000). The properties of cellular materials 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 & Kleis 1964; Persson 1987). These physical properties are also different at different heights of the plant stalk and loading rates.

As well known, the resistance of plants to lodging is closely related to the mechanical properties of their stems. This fact has been reflected in many years of research on the mechanical properties of plant stems (Blahovec *et al.* 1983, 1984, 1985; Skubisz *et al.* 1989; Blahovec & Skubisz 1990; Skubisz 1996, 1998, 2001; Skubisz & Muller 1991; Skubisz & Blahovec 1997; Grundas & Skubisz 2008).

The resistance of forage stalks to bending was determined by McClelland and Spielrein (1958) and by Prince *et al.* (1969). These investigations showed a linear relationship between the ultimate force and weight per unit length of the stalk using two-inch specimens. Curtis and Hendrick (1969) found that the section modulus in bending varied with the third power of the diameter for cotton stalks of diameters ranging from 7 to 16 mm. The Young's modulus varied from 600 to 3500 MPa. O'Dogherty *et al.* (1995) showed that the Young's

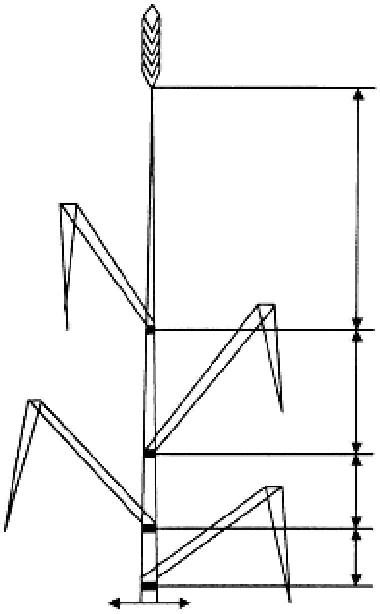

Figure 1. Diagram of straw identifying internodes

modulus for wheat straw varied between 4.76 GPa and 6.58 GPa. Chattopadhyay and Pandey (1999) found that the bending stress for sorghum stalks at the seed stage and forage stage were 40.53 MPa and 45.65 MPa, respectively.

Similar studies have been conducted in recent years such as: Ince *et al.* (2005) on sunflower stalks and Nazari Galedar *et al.* (2008) on alfalfa stems.

The objective of this study was to investigate the effects of the moisture content, internode position, and loading rate on the bending characteristics of barley straw in terms of the bending stress and Young's modulus.

MATERIAL AND METHODS

The barley stems (cv. Nosrat) used for the present study came from one of the prevalent varieties of barley in Iran and were obtained from the agronomy farm of the Seed and Seedling Research Institute, Karaj, Iran. The stems were collected at harvest and their internodes were separated according to their position down wards from the ear (Figure 1) (Annoussamy *et al.* 2000). The leaf blades and sheaths were removed prior to any treatment or measurement. To determine the average moisture content of the barley stems, the specimens were weighed and oven-dried at 103°C for 24 h (ASAE 2006) and then reweighed. To obtain stems with different moisture contents, a fine spray of water was applied using a spray gun. The duration of spray was varied to obtain stems with different moisture contents. The quantity of water which should be added to the stems was determined by the following equation (Shaw & Tabil 2006):

$$m_w = \frac{m_i(M_{wf} - M_{wi})}{1 - M_{wf}} \quad (1)$$

where:

m_w – amount of water added to the sample (g)

m_i – initial weight of the sample (g)

M_{wf} – final desired moisture content of the sample (% wet basis)

M_{wi} – initial moisture content of the sample (% wet basis)

The rewetted samples were then transferred to separate plastic bags and the bags were sealed tightly. The samples were kept at 5°C in a refrigerator for a week to enable the moisture to distribute uniformly throughout the samples. After that, the specimens were taken out of the refrigerator and allowed to warm up to room temperature for about 2 h. The specimens were then reweighed to specify the amounts of water absorbed by them. On calculating the amounts of water absorbed and using Eq. (1), the moisture contents of the straw specimens were obtained. The experiments were conducted at moisture levels of 10%, 15%, and 20% wet basis. Three internodes of barley stem, namely the first, second, and third internodes were studied in this research (Figure 1). The fourth and further stem internodes from the ear were not investigated because these internodes are usually left on the field. The experiments were also done at loading rates of 5, 10, and 15 mm/min.

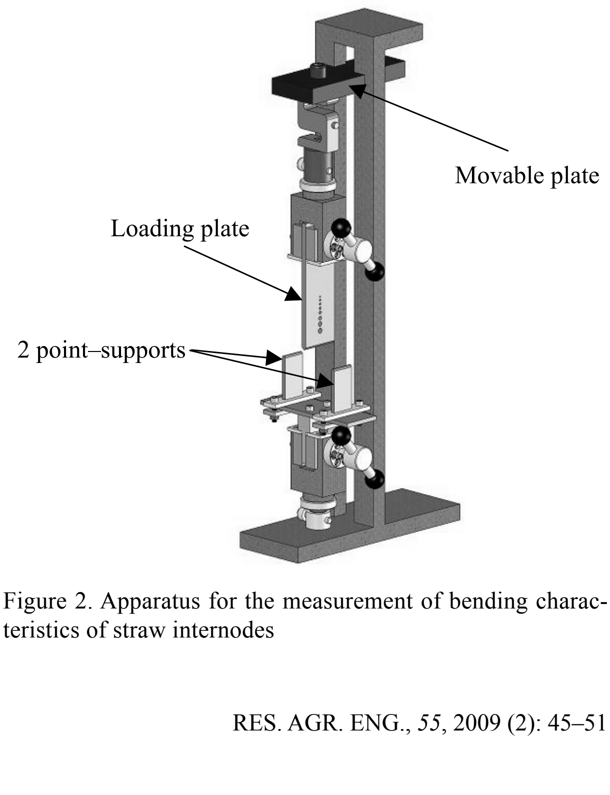

Figure 2. Apparatus for the measurement of bending characteristics of straw internodes

Table 1. Physical characteristics of barley straw in different moisture contents and internode positions (N = 15)

	Moisture content (% wet basis)								
	10			15			20		
Height	IN1	IN2	IN3	IN1	IN2	IN3	IN1	IN2	IN3
d_1 (mm)	3.75 (0.15)*	4.59 (0.26)	4.98 (0.51)	3.79 (0.16)	4.89 (0.41)	5.11 (0.34)	3.88 (0.14)	5.02 (0.31)	5.18 (0.45)
d_2 (mm)	3.33 (0.15)	4.15 (0.21)	4.30 (0.29)	3.40 (0.14)	4.21 (0.23)	4.39 (0.25)	3.49 (0.16)	4.33 (0.19)	4.58 (0.25)
t (mm)	0.26 (0.03)	0.31 (0.04)	0.36 (0.05)	0.29 (0.02)	0.33 (0.02)	0.35 (0.04)	0.30 (0.03)	0.36 (0.05)	0.38 (0.06)
I_b (mm^4)	3.37 (0.59)	7.66 (1.58)	10.09 (3.14)	3.72 (0.42)	8.39 (1.45)	10.37 (2.11)	3.96 (0.49)	9.17 (1.35)	11.87 (2.89)

*Figures in parentheses are standard deviations; N – number of observations; IN1, IN2 and IN3 – first, second and third internodes, respectively; d_1, d_2 – major and minor diameters; t – thickness of stem; I_b – second moment of area

Experimental procedure

The mechanical properties of barley straw were assessed using a three-point bending test similar to those described by Crook and Ennos (1994), Annoussamy *et al.* (2000), and Nazari Galedar *et al.* (2008) (Figure 2). The measurements were made using a proprietary tension/compression testing machine (Instron Universal Testing Machine/SMT-5, SANTAM Company, Tehran, Iran).

Bending test

To determine the Young's modulus and maximum bending stress, the specimens were arranged with their major axis of the cross-section in the horizontal plane and placed on two rounded metal supports located 50 mm apart and then loaded in the midway between the supports with a blade driven by movable supports (Figure 2). The edge radius of the supports and blade was 0.3 mm. The force applied was meas-

Table 2. Mean comparison of bending stress and Young's modulus of barley straw at different moisture contents, loading rates and internode positions

	Bending stress (MPa)	Young's modulus (MPa)
Moisture content (% wet basis)		
10	9.907^{a*}	561.667^{a}
15	8.347^{b}	470.448^{b}
20	6.980^{c}	389.528^{c}
Loading rate (mm/min)		
5	7.872^{a}	446.431^{a}
10	8.446^{b}	475.360^{b}
15	8.916^{b}	499.851^{c}
Internode position		
IN1	9.260^{a}	508.592^{a}
IN2	8.198^{b}	466.664^{b}
IN3	7.775^{b}	446.386^{c}

*The means with minimum common letter are not significantly different (P > 0.05) according to Duncan's multiple ranges test ured by the strain-gauge load cell and force-time record obtained up to the failure of the specimen. As shown in Table 1, most specimens were slightly elliptical in the cross-section, thus the second moment of the area in bending about the major axis (I_b) was calculated as (Gere & Timoshenko 1997):

$$I_b = \frac{\pi}{4}\left[ab^3 - (a-t) \times (b-t)^3\right] \quad (2)$$

where:
I_b – second moment of area (mm^4)
a – semi-major axis of the cross–section (mm)
b – semi-minor axis of the cross-section (mm)
t – mean wall thickness (mm)

The Young's modulus, E, was calculated from the following expression for a simply supported beam located at its centre (Gere & Timoshenko 1997):

$$E = \frac{F_b l^3}{48\delta l_b} \quad (3)$$

where:
E – Young's modulus (MPa)
F_b – bending force (N)
l – distance between the two metal supports (mm)
δ – deflection at the specimen centre (mm)

Maximum bending stress, σ_b, has been defined by (Crook & Ennos 1994; Gere & Timoshenko 1997):

$$\sigma_b = \frac{F_b a l}{4 I_b} \quad (4)$$

where:
σ_b – bending stress (MPa)

Experimental design and statistical analysis

This study was planned as a completely randomised block design. The experiments were conducted with five replications in each test. The experimental data were analysed using the analysis of variance (ANOVA) and the means were separated at the 5% and 1% probability levels applying Duncan's multiple range tests in SPSS software (vers. 15, SPSS, Inc., Chicago, IL, USA).

RESULTS AND DISCUSSION

The variance analysis of the data indicated that the moisture content, internode position, and loading rate have a significant effect on the bending stress and Young's modulus ($P < 0.01$). The average bending stress was obtained as 8.41 MPa varying from 6.32 to 12.41 MPa, while the average Young's modulus was calculated as 473.88 MPa ranging from 330.94 to 618.91 MPa. Based on the statistical analysis, the interaction effects of the moisture content × loading rate, internode × loading rate, and moisture content × internode × loading rate on the bending stress and Young's modulus were not significant ($P > 0.05$). The interaction effect of the moisture content × internode on the bending stress was significant at 5% probability level but the effect on the Young's modulus was not significant ($P > 0.05$).

In the following paragraphs, the effects of each factor on the bending stress and Young's modulus are comprehensively discussed.

Moisture content

The moisture content had a significant effect ($P < 0.01$) on the bending stress and Young's modulus as shown in Table 2. The bending stress and Young's modulus decreased with an increase in the moisture content indicating a reduction in the brittleness of the stem. Such a result was also reported by Ince *et al.* (2005) for sunflower stalk and Nazari Galedar *et al.* (2008) for alfalfa stem. The bending stress of

Table 3. Mean comparison of bending stress and Young's modulus of barley straw considering interaction effect of moisture content and internode position

Moisture content (% wet basis)	Internode position					
	bending stress (MPa)			Young's modulus (MPa)		
	IN1	IN2	IN3	IN1	IN2	IN3
10	11.475[a*]	9.484[b]	8.761[bc]	592.64[a]	558.07[b]	534.29[bc]
15	8.856[bc]	8.239[cd]	7.947[cd]	509.70[c]	459.64[d]	442.00[de]
20	7.450[de]	6.872[e]	6.618[e]	423.44[e]	382.28[f]	362.86[f]

*The means with minimum common letter are not significantly different ($P > 0.05$) according to Duncan's multiple ranges test barley straw decreased from 11.47 to 7.45 MPa, 9.48 to 6.87 MPa, and 8.76 to 6.62 MPa for the first, second, and third internodes, respectively, as the moisture content increased. The Young's modulus of the straw also varied from 423.44 to 592.64 MPa, 382.28 to 558.07 MPa, and 362.86 to 534.29 MPa for the first, second, and third internodes, respectively, at different moisture contents studied. The values of the bending stress, as obtained in the current study for barley straw, were lower than that of sorghum stalk (45.65 MPa) at the forage stage and those of alfalfa stems (9.71 to 47.49 MPa) in the moisture content range of 10 to 80% wet basis (Chattopadhyay & Pandey 1999; Nazari Galedar *et al.* 2008). Furthermore, the values of the bending stress for barley straw were close to those of wet wheat straw (6.4 to 10.5 MPa), and were lower than those of dry wheat straw (15.0 to 26.9 MPa) (Annoussamy *et al.* 2000). Therefore, barley straw is more flexible in comparison with sorghum stalk, alfalfa stem, and wheat straw.

The values of the Young's modulus for barley straw were found to be lower than those of wheat straw (4.76 to 6.58 GPa) and of alfalfa stems (0.63 to 4.60 GPa) (O'Dogherty *et al.* 1995; Nazari Galedar *et al.* 2008). The interaction effect of moisture content × internode on the bending stress and Young's modulus is presented in Table 3.

Loading rate

The mean values of the bending stress and Young's modulus at different loading rates are presented in Table 2. It was observed that the bending stress and Young's modulus of the straw increased significantly ($P < 0.01$) with an increase in the loading rate. Such an effect of the loading rate was also reported by El Hag *et al.* (1971) for cotton stalk. Mohsenin *et al.* (1963) also found that the rate of deformation affected the maximum force that could be exerted by a steel plunger on apples. As the rate of deformation increased, the maximum force of rupture increased. The bending stress of barley straw increased from 8.53 to 9.84 MPa, 7.75 to 8.73 MPa, and 7.33 to 8.18 MPa for the first, second and third internodes, respectively, as the loading rate increased from 5 to 15 mm/min. The Young's modulus of the straw varied from 419.03 to 538.84 MPa in the third internode under the lowest loading rate, and the first internode under the highest loading rate, respectively. The interaction effect of the loading rate × internode on the bending stress and Young's modulus is presented in Table 4.

Internode position

The bending stress and Young's modulus were significantly affected by the internodes at 1% probability level. The values decreased towards the third internode position. The mean values of the characteristics with different internodes are presented in Table 2. It was observed that the bending stress and Young's modulus of the straw decreased from 9.26 to 7.77 MPa, and 508.59 to 446.38 MPa, respectively, towards the third internode position. A similar effect of the stem level on the bending stress and Young's modulus was also reported by Ince *et al.* (2005) for sunflower stalk and Nazari Galedar *et al.* (2008) for alfalfa stems. The interaction effects of the internode × moisture content and internode × loading rate on the bending stress and Young's modulus are presented in Table 3 and 4, respectively.

The equations representing the relationships between the bending stress and Young's modulus of barley straw and the moisture content and loading rate for each internode position and their respective coefficients of determination (R^2) are presented in Table 5.

Table 4. Mean comparison of bending stress and Young's modulus of barley straw considering interaction effect of loading rate and internode position

Loading rate (mm/min)	Internode position					
	bending stress (MPa)			Young's modulus (MPa)		
	IN1	IN2	IN3	IN1	IN2	IN3
5	8.533^{bc*}	7.750^{cd}	7.332^{d}	482.41^{bcd}	437.85^{ef}	419.03^{f}
10	9.405^{ab}	8.114^{cd}	7.818^{cd}	504.52^{b}	470.19^{cde}	451.37^{de}
15	9.842^{a}	8.731^{bc}	8.176^{cd}	538.84^{a}	491.96^{bc}	468.76^{cde}

*The means with minimum common letter are not significantly different ($P > 0.05$) according to Duncan's multiple ranges test

Table 5. Equations representing relationships between bending stress and Young's modulus of barley straw and moisture content and loading rate for each internode position

Treatments	Internode position	Bending stress (MPa)	R^2	Young's modulus (MPa)	R^2
Moisture content	IN1	$\sigma_b = 17.42 \times \exp(-0.04\,Mc)$	0.986	$E = -16.92 \times Mc + 762.3$	0.999
	IN2	$\sigma_b = 13.17 \times \exp(-0.03\,Mc)$	0.994	$E = -17.57 \times Mc + 730.3$	0.995
	IN3	$\sigma_b = 11.76 \times \exp(-0.02\,Mc)$	0.970	$E = -17.14 \times Mc + 703.5$	0.998
Loading rate	IN1	$\sigma_b = 0.130 \times R_L + 7.951$	0.964	$E = 5.643 \times R_L + 452.1$	0.984
	IN2	$\sigma_b = 0.098 \times R_L + 7.217$	0.978	$E = 5.411 \times R_L + 412.5$	0.987
	IN3	$\sigma_b = 0.084 \times R_L + 6.931$	0.992	$E = 4.973 \times R_L + 396.6$	0.970

R^2 – determination correlation; E – Young's modulus; Mc – moisture content; R_L – loading rate; σ_b – bending stress

This paper concludes with the information on the engineering properties of barley straw which may be useful for designing the equipment used for harvesting, threshing, and processing. It is recommended that other engineering properties such as the coefficient of friction, bulk density, shear strength, shearing energy, tensile strength, rigidity modulus, and Poisson's ratio should be measured or calculated to provide fairly comprehensive information on the design parameters involved in barley straw harvesting and processing.

CONCLUSIONS

The following conclusions are drawn from the investigation of the effects of the moisture content, internode position, and loading rate on the bending stress and Young's modulus of barley straw.

Both the bending stress and Young's modulus decreased with an increase in the moisture content and towards the third internode position and increased with the increasing loading rate.

The bending stress varied from 6.32 to 12.41 MPa and the Young's modulus ranged from 330.94 to 618.91 MPa.

The bending stress of barley straw decreased from 11.47 to 7.45 MPa, 9.48 to 6.87 MPa, and 8.76 to 6.62 MPa for the first, second, and third internodes, respectively, as the moisture content increased. The Young's modulus of the straw also varied from 423.44 to 592.64 MPa, 382.28 to 558.07 MPa, and 362.86 to 534.29 MPa for the first, second, and third internodes, respectively, at different moisture contents studied.

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Abstrakt

Tavakoli H., Mohtasebi S.S., Jafari A. (2009): **Vliv obsahu vlhkosti, polohy internodia a zátěžové rychlosti na ohybové vlastnosti ječné slámy**. Res. Agr. Eng., **55**: 45–51.

Cílem studie bylo stanovení vlivu vlhkosti, polohy internodia a zátěžové rychlosti na ohybové vlastnosti ječné slámy včetně ohybového napětí a Youngova modulu. Ve studii bylo provedeno 9 pokusů v náhodném kompletním blokovém uspořádání s pěti replikacemi. Stanovení vlastností bylo provedeno při třech hladinách vlhkosti 10 %, 15 % a 20 %, při třech zátěžových rychlostech 5, 10 a 15 mm/min, a se třemi internodii, prvním, druhým a třetím shora. Bylo zjištěno, že napětí v ohybu a Youngův modulus klesaly při vyšším obsahu vlhkosti a směrem ke třetímu internodiu. Průměrné napětí v ohybu bylo 8,41 MPa při rozsahu od 6,32 do 12,41 MPa, průměrná hodnota Youngova modulu byla 473,88 MPa a rozsah od 330,94 do 618,91 MPa. Výsledky ukázaly, že hodnoty sledovaných vlastností se zvyšovaly s rostoucí zátěžovou rychlostí.

Klíčová slova: ječmen; obsah vlhkosti; zátěžová rychlost; napětí v ohybu; Youngův modulus

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