# Comparison of Mechanical Properties of Wheat and Barley Straw

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## ABSTRACT

The objective of this work was to compare the mechanical properties of wheat and barley straw. The experiments were conducted at moisture contents of 10.24% and 10.76% w.b. for wheat and barley straw, respectively, and three internode positions down from the ear. The average shear strength for wheat and barley straw varied from 6.81 to 7.12 MPa and 3.90 to 4.49 MPa, respectively. The specific shearing energy of wheat and barley straw increased from 21.85 to 25.74 mJ/mm$^2$ and 18.79 to 19.85 mJ/mm$^2$, respectively, towards the third internode position. The bending stress and Young's Modulus of wheat and barley straw increased towards the first internode position. The results showed that the mechanical properties of wheat and barley straw were statistically different.

Keywords: Straw, barley, wheat, Young's modulus, shear strength, specific shearing energy

## 1. INTRODUCTION

In Iran, wheat and barley are widely cultivated on approximately 6 941 286 and 1 817 572 ha with an annual production of 14 000 and 2 900 Kt, respectively (FAO, 2006); several tons straw produce from these crops annually; these straws usually serve as an animal nutrition and sometimes incorporate into the plowed layer or use as a mulch. For these purposes, straw must be processed (e.g. threshing, handling, etc.) after harvesting. For selecting design and operational parameters of equipment relating to harvesting, threshing, handling and other processing of wheat and barley straw, we need knowledge of physical and mechanical properties of them.

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 & Moshenin, 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 & 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 of mechanical and rheological properties of agricultural products have been described by Mohsenin (1986).

Several works have been conducted to determine the mechanical properties of plants. 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 maxima at moisture contents of 20% w.b. and 35% w.b. for the two sets of data. The form 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. O'Dogherty et al. (1995) measured the shear strength of six varieties of wheat straw and found mean values in the range 5.4–8.5 MPa. Kushwaha et al. (1983) reported mean values of shear strength of wheat straw in the range 8.6 -13.0 GPa 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 & 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 & 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 & Erbach (1986). Sakharov et al. (1984) reported that the required force to cut stretched (bent) stalks was 50% less than that for straight stalks.

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 ultimate force and weight per unit length of stalk using a two-inch specimen. Curtis and Hendrick (1969) determined 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 modulus for wheat straw varied between 4.76 GPa and 6.58 GPa. Chattopadhyay and Pandey (1999) found that the bending stress for sorghum stalk at the seed stage and forage stage was 40.53 MPa and 45.65 MPa, respectively.

Similar works have been conducted in recent years such as: Chen et al. (2004) on hemp stem, İnce et al. (2005) on sunflower stalk and Nazari Galedar et al. (2008) on alfalfa stems. It seems that there is not published work relating to comparison of mechanical properties of wheat and barley straw. Therefore, the objective of this study was to compare mechanical properties of wheat and barley straw, namely, shear strength, specific shearing energy, bending stress and Young's modulus.

| Nomenclature | | | |
|---|---|---|---|
| $A$ (mm$^2$) | cross –section area of wall | $F_s$ (N) | shear force |
| $a$ (mm) | semi major diameter | $I_b$ (mm$^4$) | second moment of area |
| $b$ (mm) | semi minor diameter | $l$ (mm) | length of specimen |
| $E$ (GPa) | Young's modulus | $t$ (mm) | wall thickness |
| $E_s$ (mJ) | shearing energy | $\delta$ (mm) | deflection at the specimen centre |
| $E_{sc}$ (mJ/mm$^2$) | specific shearing energy | $\sigma_b$(MPa) | bending stress |
| $F_b$ (N) | bending force | $\tau_s$ (MPa) | shear strength |

## 2. MATERIALS AND METHODS

The wheat and barley stem, variety Alvand and Nosrat, respectively, used for the present study was obtained from agronomy farm of the Seed and Seedling Research Institute, Karaj, Iran. The stems were collected at harvest and their internodes were separated out according to their position down from the ear (Fig. 1) (Annoussamy et al. 2000). Leaf blades and sheaths were removed prior to any treatment or measurement. To determine the average moisture content of the wheat and barley stems, the specimens were weighed and oven-dried at 103 ˚C for 24 h (ASAE, 2006) and then reweighed. The average moisture contents of the wheat and barley stems were 10.24% and 10.76% w.b., respectively.

The experiments were conducted at moisture contents above and three internode positions of wheat and barley stem, namely, first, second and third internode position (Fig. 1). The fourth and other stem internodes from the ear were not investigated because these internodes usually are left on the field.

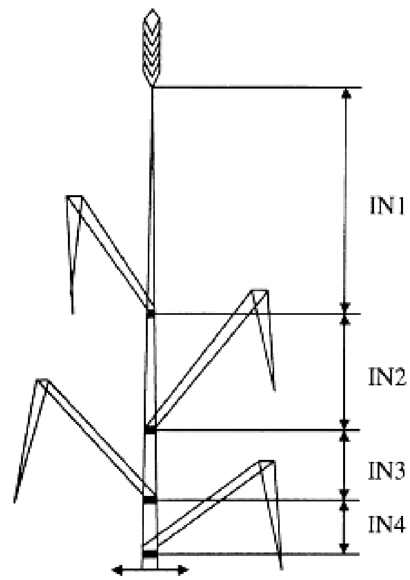


Fig.1. Diagram of straw identifying internodes

### 2.1. Experimental procedure

The mechanical properties of wheat and barley straw were assessed using a shearing test similar to those described by O'Dogherty et al. (1995), İnce et al. (2005) and Nazari Galedar et al. (2008) (Fig. 2a) and a three-point bending test similar to those described by Crook and Ennos (1994), Annoussamy et al. (2000) and Nazari Galedar et al. (2008) (Fig. 2b). The measurements were made using a proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Tehran, Iran).

#### 2.1.1. Shearing test

The shear strength was measured in double shear using a shear box (Fig. 2a) 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 diameter ranging from 1.5 to 5 mm were drilled through the plates to accommodate internodes of differing diameter. Shear force was applied to the straw specimens by mounting the shear box in the tension/compression testing machine. The sliding plate was loaded at a range of 10 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), $\tau_s$, of the specimen was calculated from:

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

Where $F_s$ is the shear force at failure and $A$ is the wall area of the specimen at the failure cross-section. The shearing energy was calculated by integrating the curves of shear force and displacement (Chattopadhyay & Pandey, 1999; Chen et al., 2004; Nazari Galedar et al., 2008) using a standard computer program (vers. 5, SMT Machine Linker, SANTAM Company, Tehran, Iran). The specific shearing energy, $E_{sc}$ was found by:

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

Where $E_s$ is the shearing energy.

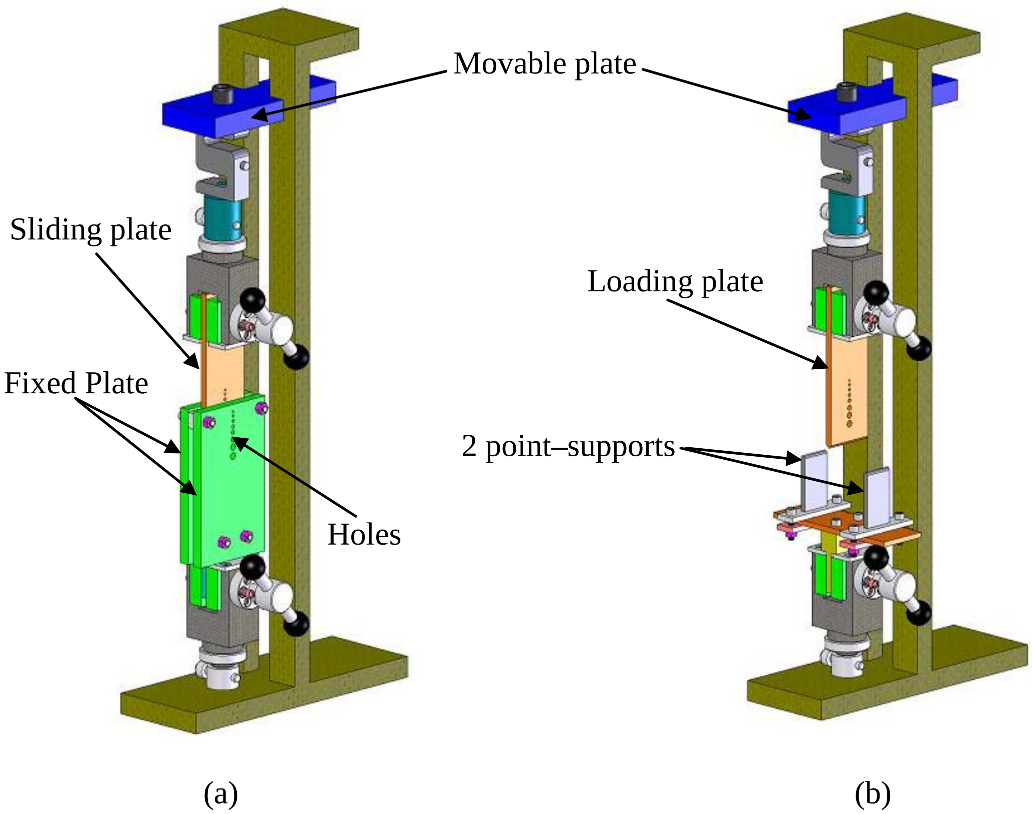


Fig.2. Apparatus for the measurement of a) shearing strength, and b) bending strength of straw internodes

**2.1.2. Bending test**

To determine of Young's modulus and maximum bending stress, the specimens were arranged with the major axis of the cross-section in the horizontal plane and placed on two rounded metal supports 50 mm apart and then loaded midway between the supports with a blade driven by the movable supports (Fig. 2b). The loading rate was 10 mm min$^{-1}$ and the force applied was measured by a strain-gauge load cell and a force-time record obtained up to the failure of the specimen. Most specimens were slightly elliptical in cross-section and second moment of area in bending about a major axis ($I_b$) was calculated as (Gere & Timoshenko, 1997):

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

Where $a$ is the semi-major axis of the cross–section, $b$ is the semi-minor axis of the cross-section and $t$ is the mean wall thickness. The Young's modulus, $E$, was calculated from the following expression for a simply supported beam located at its centre (Gere & Timoshenko, 1997):

$$E = \frac{F_b l^3}{48\delta I_b} \tag{4}$$

Where $F_b$ is the bending force, $l$ is the distance between the two metal supports, $\delta$ is the deflection at the specimen centre and $I_b$ is the second moment of area. Maximum bending stress, $\sigma_b$, is defined by (Gere & Timoshenko, 1997; Crook & Ennos, 1994):

$$\sigma_b = \frac{F_b a l}{4 I_b} \tag{5}$$

Where $a$ is the semi-major axis of the cross–section.

### 2.2. Experimental design and statistical analysis

This study was planned as a completely randomized block design. Five replications were made in each treatment for mechanical properties of the stems. Experimental data were analysed using analysis of variance (ANOVA) and the means were separated applying Duncan's multiple range tests in SPSS 13 software.

## 3. RESULTS AND DISCUSION

### 3.1. Shear strength

The mean values for shear strength of wheat and barley straw at different stem internode positions are presented at Table 1. Its values varied from 6.81 to 7.12 MPa and 3.90 to 4.49 MPa for wheat and barley straw, respectively. The shear strength for both of wheat and barley straw increased towards the third internode position. Similar result was reported by most previous researchers (İnce et al., 2005; Nazari Galedar et al., 2008). As shown in Fig. 3 the shear strength values for wheat straw are greater than those of barley straw at all internode positions. The shear strength values of wheat straw showed significant differences from those of barley straw at 5% probability level. The greater values of the shear strength for wheat straw in comparison with barley straw indicate that the wheat straw has more shearing resistance.

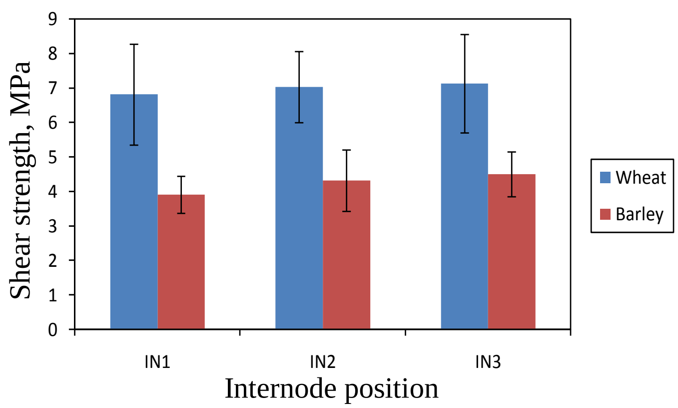


Fig.3. Diagram of shear strength for wheat and barley straw at different internode positions.

### 3.2. Specific shearing energy

The values of the specific shearing energy varied from 21.85 to 25.74 mJ/mm$^2$ and 18.79 to 19.85 mJ/mm$^2$ for wheat and barley straw, respectively (Table 1). The specific shearing energy of wheat and barley straw increased towards the third internode position. It was greater in the third internode because of the accumulation of more mature fibres in the stem (İnce et al., 2005). This effect of plant height on shearing energy requirement was also reported by Annoussamy et al. (2000) for wheat straw, İnce et al. (2005) for sunflower stalk and Nazari Galedar et al. (2008) for alfalfa stem. According to the Duncan's multiple range tests, the values of the specific shearing energy for wheat straw were significantly greater (*P*<0.05) than those of barley straw (Fig. 4). This means that the energy requirement for shearing of wheat straw is more than barley straw.

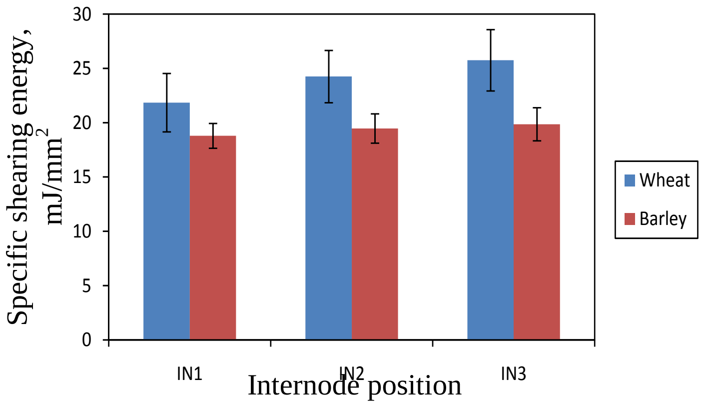


Fig.4. Diagram of specific shearing energy for wheat and barley straw atdifferent internode positions.

Table 1-Mechanical properties of wheat and barley internodes

| | Wheat | | | Barley | | |
|---|---|---|---|---|---|---|
| height | IN1 | IN2 | IN3 | IN1 | IN2 | IN3 |
| N* | 5 | 5 | 5 | 5 | 5 | 5 |
| $\tau_s$ (MPa) | $6.81_a$ (1.46)** | $7.02_a$ (1.03) | $7.12_a$ (1.42) | $3.90_b$ (0.53) | $4.31_b$ (0.88) | $4.49_b$ (0.64) |
| $E_{sc}$(mJ/mm$^2$) | $21.85_{bc}$ (2.68) | $24.25_{ab}$ (2.41) | $25.74_a$ (2.82) | $18.79_d$ (1.13) | $19.47_{cd}$ (1.34) | $19.85_{cd}$ (1.52) |
| $\sigma_b$ (MPa) | $19.31_a$ (2.59) | $14.95_b$ (0.92) | $13.70_b$ (1.71) | $8.55_c$ (1.10) | $8.39_c$ (0.75) | $8.14_c$ (1.37) |
| E (GPa) | $1.82_a$ (0.45) | $1.05_b$ (0.31) | $0.98_b$ (0.18) | $0.53_c$ (0.04) | $0.50_c$ (0.09) | $0.44_c$ (0.06) |

*N: observation number
** Figures in parentheses are standard deviation. a-d: means followed by different letters are significantly different from others in the same line (P < 0.05).

### 3.3. Bending stress

The bending stress varied from 13.70 to 19.31 MPa and 8.14 to 8.55 MPa for wheat and barley straw, respectively (Table 1). The bending stress of wheat and barley straw increased towards the first internode position. Similar trend of increasing was reported by Annoussamy et al. (2000) for wheat straw and Nazari Galedar et al. (2008) for alfalfa stem. As shown in Fig. 5 the shear strength values for wheat straw are significantly greater ($P$<0.05) than those of barley straw at all internode positions. The greater values of the bending stress for wheat straw in comparison with barley straw indicate that the wheat straw is more brittle.

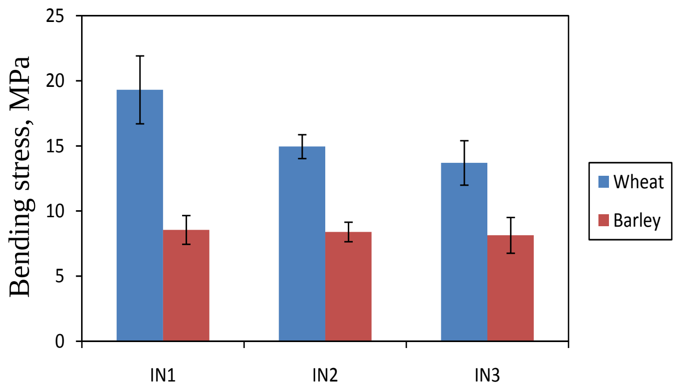


Fig.5. Diagram of bending stress for wheat and barley straw at different internode positions.

### 3.4. Young's modulus

The Young's modulus in bending for wheat and barley straw increased towards the first internode position. Similar result was reported by Annoussamy et al. (2000) for wheat straw and Nazari Galedar et al. (2008) for alfalfa stem. The range of values was from 0.98 to 1.82 GPa and 0.44 to 0.53 GPa for wheat and barley straw, respectively (Table 1). According to the Duncan's multiple range tests, the values of the Young's modulus for wheat straw were significantly greater ($P$<0.05) than those of barley straw (Fig. 6). The average value of the Young's modulus for wheat straw was around 2.5 times greater than that of barley straw.

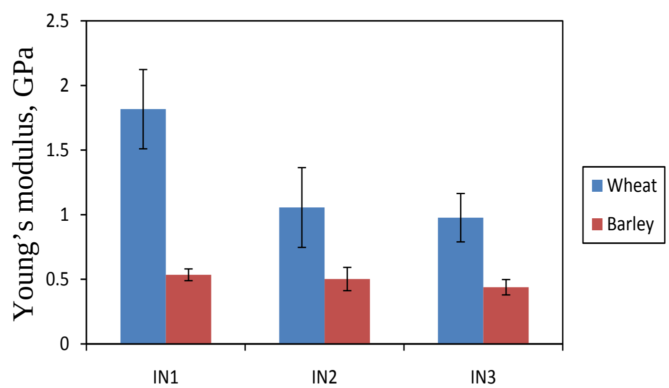


Fig.6. Diagram of Young's modulus for wheat and barley straw at different internode positions.

## 4. CONCLUSIONS

In this study, the mechanical properties of wheat and barley straw at three internode positions were compared. Results showed that the shear strength and specific shearing energy increased towards the third internode position, while the bending stress and Young's modulus decreased, for both of wheat and barley straw. The mechanical properties of wheat and barley straw were statistically different. The average shear strength, specific shearing energy, bending stress and Young's modulus for wheat were around 1.5, 1.5, 2 and 2.5 times greater than those of barley straw. These results indicate that threshing of wheat straw requires more energy than barley straw.

## 5. ACKNOWLEDGMENTS

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