Bending and Shearing Characteristics of Alfalfa Stems

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ABSTRACT

Bending stress, young's modulus, shearing stress and shearing energy were determined for Alfalfa (*Medicago Sativa* L.) stem. The bending forces were measured at different moisture contents and the bending stress and the young's modulus were calculated from these data. For measuring the shearing forces, the stem specimens were severed by using a computer aided cutting apparatus. The shearing energy was calculated by using the area under the shearing force versus displacement curve. The experiments were conducted at a moisture content of 10%, 20%, 40% and 80% w.b. The bending stress decreased as the moisture content increased. The value of the bending stress at low moisture content was obtained approximately 3 times higher than at high moisture content. The average bending stress value varied from 9.71 to 47.49 MPa. The young's modulus in bending also decreased as the moisture content and diameter of stalks increased. The average young's modulus ranged from 0.79 to 3.99GPa. The results showed that the shearing stress and the shearing energy increased as the moisture content increased. The maximum shear strength and shearing energy were found to be 28.16 MPa and 345.80 mJ, respectively. Both the shearing stress and the specific shearing energy were found to be higher in the lower region of the stalk due to structural heterogeneity.

Keywords: Alfalfa, bending stress, young's modulus, shearing stress, shearing energy, Iran

1. INTRODUCTION

Alfalfa, an excellent source of protein, vitamins and minerals is the most important forage crop species in Iran. Information about the physical and mechanical properties of alfalfa stem is very important in the design of machines such as mowers, balers and choppers. The lack of knowledge about physical properties of alfalfa stem has been pointed out by engineers concerned with forage cutting device (McClelland and Spielrein, 1958; Prince, 1961). One of the primary reasons for this lack of information about the physical characteristic of forage materials is the wide variation that exists in their properties. Another reason is the absence of the proven procedure and kindred test equipment for use in defining these properties (El Hag et al., 1971). Most studies on the mechanical properties of plants have been done during their development using failure criteria (force, stress and energy) or the young's modulus. They have focused on plant anatomy, lodging processes, harvest optimization, animal nutrition, industrial application and decomposition of wheat straw in soil (McNulty and Moshenin, 1979; Annoussamy et al., 2000; Hirai et al., 2002). The physical properties of the cellular material are importances in cutting, compression, tension, bending, density and friction (Shaw and Tabil, 2007; Yiljep and Mohammed, 2005). These properties depend on 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. Hence, it is necessary to determine the physico–mechanical properties such as the bending and shearing stress and energy requirements for suitable knife design and operational parameters (İnce et al., 2005). Hall et al. (1967) studied the viscoelastic properties of alfalfa stems they found that alfalfa stems be have as viscoelastic materials, rather than viscoplastic materials. Halyk (1962) determined the tensile and shear strength of alfalfa stems and developed regression equations relating tensile strength to moisture and density.

Dernedde (1970) used a shear box method to measure shear strength of an assemblage of forage materials; in two series of experiments, he found ranges of 25–88 MPa and 59–128 MPa, with maxima at moisture contents of 20% and 35% for two sets of data. The form of the curves relating shear strength to moisture content is analogous to those found by Liljdall et al. (1961) for the specific energy required to cut beds of forage. Measurement of the shear strength of six varieties of wheat straw by O'Dogherty et al. (1995) showed mean values in the range 5.4–8.5 MPa. Kushwaha et al. (1983) reported mean values of shear strength of wheat straw from 8.6 to 13.0 GPa with some dependence on moisture content. Other workers have measured the energy require to shear materials. McRandal and McNulty (1980) conducted shearing experiments on field grasses and found that the shearing stress was 16 MPa and the shearing energy was 12.0 $mJmm^{-2}$. Prasad and Gupta (1975) emphasized that the cross-sectional area and moisture content of the crop had significant effect on cutting energy and maximum cutting force. Similar results were also reported by Choi and Erbach (1986). Sakharov et al. (1984) reported that the required force to cut the stretched stalks was 50% less than that of unbent stalks. Chen et al. (2004) found that the average values of the maximum force and the total cutting energy for hemp were 243N and 2.1 J, respectively. 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 3500MPa. O'Dogherty et al. (1995) has shown that the young's modulus for wheat straw had a magnitude of 4.76 to 6.58 GPa. Chattopadhyay and Pandey (1999) determined the bending stress for sorghum stalk as 40.53 and 45.65MPa at the seed stage and forage stage, respectively. There are no studies on bending stress of alfalfa stem and lack of information about young's modulus. The aim of this study to measure bending and shearing characteristics of alfalfa stem and determine of the relationship between these properties with moisture content and height regions of alfalfa stem.

2. MATERIALS AND METHODS

The research was conducted in order to determine the bending stress, the young's modulus, the shearing stress and the shearing energy of alfalfa stem as a function of moisture content and height regions. To determine the average moisture contents of the alfalfa stem on the date of the test, the specimens gathered from the field were weighed and dried at 103˚ C for 24 h (ASAE, 2006a) in the oven and reweighed. The experiments were conducted at a moisture content of 10%, 20%, 40% and 80% w.b. The diameter of the alfalfa stem decreases towards the top of the plant. Therefore, it was divided equally into three height regions as upper, middle and lower. The average major diameter of the stems in the upper, middle and lower regions varied between 1.97–2.60, 3.49–3.72 and 3.41–4.04 mm, respectively. The average minor diameter of the stems in the upper, middle and lower regions varied between 1.61–2.25, 2.77–3.36 and 3.11–3.89 mm, respectively.

2.1. Experimental Procedure

2.1.1. Bending Test

The stiffness of stems encountered during harvesting depends on the rigidity of materials. The modulus of rigidity of stalk is expressed by the product *EI*, where *E* is the young's modulus in bending in MPa and *I* is the moment of inertia of cross-sectional area in mm^4 (Kanafojiski and Karwowski, 1972). For determination of young's modulus, the stems were arranged with the major axis of the cross–section in the horizontal plane and placed on two rounded metal supports 50mm apart and then loaded midway between the supports with a blade driven by the movable supports(Fig. 1). The loading rate was 10mm/min and the bending force was measured by a strain-gage 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 and timoshenko, 1997):

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

where *a* is the semi major axis of the cross–section in mm, where *b* is the semi minor axis of the cross-section in mm and *t* is the mean wall thickness in mm. Young's modulus of alfalfa was assessed using a three–point bending test similar to those described by Crook and Ennos (1994) (Fig.1). The young modulus, *E*, was calculated from the expression obtained from Crook and Ennos (1994) for a simply supported beam located at its center:

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

where F_b is the apply load in N, *l* is the distance between the two metal supports in mm, δ is the deflection at the specimen centre in mm and I_b the second moment of area in mm^4. Maximum bending stress, σ_b, is defined by (Gere and Timoshenko, 1997; Crook and Ennos, 1994):

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

2.1.2. Shearing Test

In order to determine the shearing force of alfalfa stems, an experimental shearing apparatus was used (Fig. 2). The shear strength was measured in double shear using a shear box (Fig. 2) consisting essentially of to 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 straw specimens of differing diameter. Shear force was applied to the straw specimens by mounting the shear box in a proprietary tension/compression testing machine. The sliding plate was loaded at a range of 10mm/min and, as for the shear test, the applied force was measured by a strain-gage 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 expression:

$$\tau_s = \frac{F_s}{2A} \tag{2}$$

where F_s is the shear force at failure in N and A is the wall area of the specimen at the failure cross-sections in mm^2. The shearing energy was calculated by using the area under curves of shear force and displacement (Chattopadhyay and Pandey, 1999; Chen et al., 2004). For this case, the area under the curve was divided into the basic geometrical shapes and the calculation of the area under the curve was made with the help of the force and displacement data by using a standard computer program.

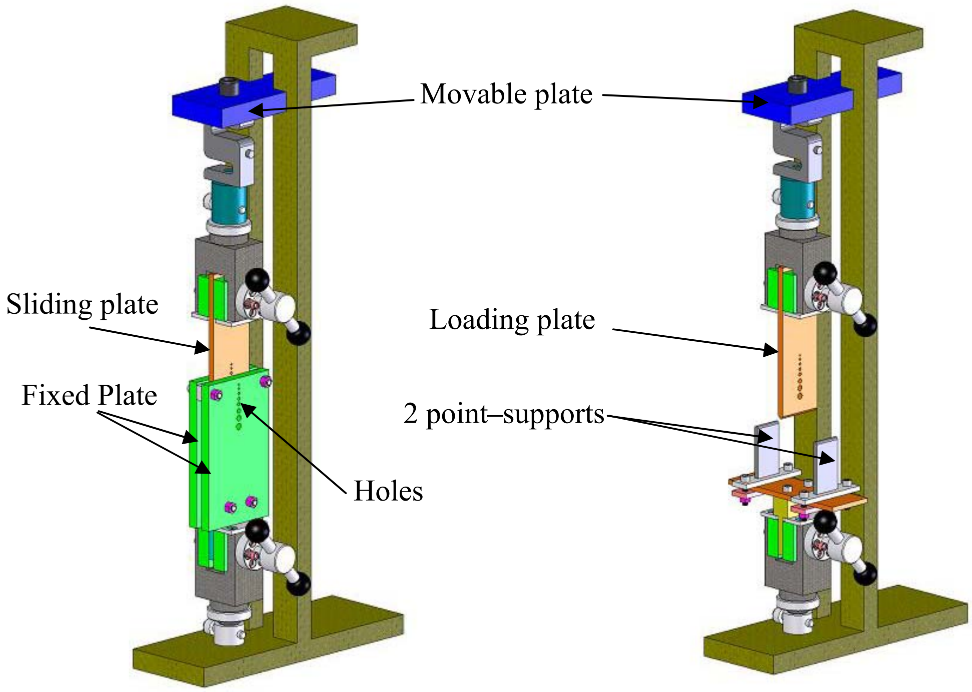

Figure.1. Apparatus for the measurement of shearing stress strength

Figure.2. Apparatus for the measurement of young modulus

3. RESULTS AND DISCUSSION

Figure 3 shows examples of the force recorded during shearing and bending tests with the distance covered by the movable support as function of height regions. The alfalfa stem is a fibrous material and has a tubular section. The shearing of the fibers is achieved by compression which causes these hollow tubes to collapse before severing the fibers. In other words, it shows the properties of solid cut after compression. The mechanical criteria considered were failure criteria (maximum force, maximum stress, energy required for failure) and Young's modulus.

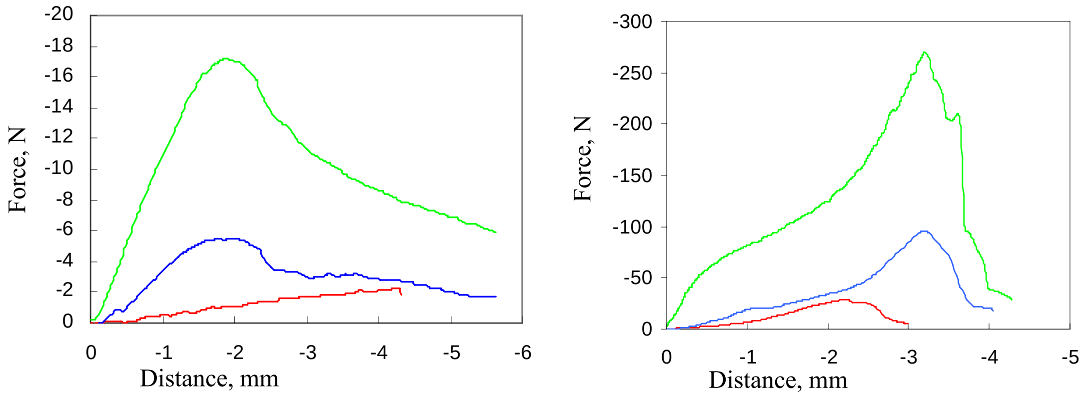

Figure 3–Force versus distance covered by the movable support during (a) bending and (b) shearing tests. (●) upper region, (●) middle region and (●) lower region

3.1. Bending Stress

Figure 4 shows examples of the force recorded during shearing and bending tests with the distance covered by the movable support. The bending stress was evaluated as a function of moisture content and height regions. As the moisture content of the stalk increased, the bending stress decreased (Fig. 4), indicating a reduction in the brittleness of the stalk. This result was also reported by Annoussamy et al. (2000). The bending stress also decreased towards the upper regions (Fig. 8). This effect of moisture content was also reported by İnce et al. (2005). The value of the bending stress at low moisture content was approximately 3 times higher than at high moisture content. Its values varied between 15.18–47.49, 11.48–40.20, and 9.71–34.83 MPa for the upper, middle and lower regions, respectively, at the different moisture contents studied. The moisture content and height regions have a significant effect on the bending stress at 0.05 probability level. Moreover, according to Duncan's multiple range test results the bending stress values are statistically different from each other. The relationship between moisture content and bending stress can be expressed by the following equation:

Upper region	$Y=0.0073x^2-1.1547x+60.628$	$(R^2=0.9647)$
Middle region	$Y=0.0081x^2-1.16.92x+53.065$	$(R^2=0.9647)$
Lower region	$Y=0.0072x^2-1.0278x+45.668$	$(R^2=0.9647)$

3.2. Young's Modulus

The young's modulus in bending was evaluated according to the moisture contents and height regions (Fig. 4). O'Dogherty et al. (1995) has shown that the young' modulus for wheat straw had a magnitude of 4.76 to 6.58 GPa. The results of O'Dogherty et al. (1995) showed that the young's modulus is reduced when internode moisture increased. The difference between the values for the young's modulus at the lowest and highest moisture contents was about 80%. The average values for the young's modulus were found to be 0.79, 1.80, 3.52 and 3.99 GPa for moisture contents of 80%, 40%, 20% and 10%, respectively. The effects of moisture content and height regions on the young's modulus were significant at 0.05 probability level. However, as seen in Fig.4, the effect of stalk diameter decreases at lower moisture contents.

The relationship between moisture content and young's modulus can be expressed by the following equation:

Upper region	$Y=0.0007x^2-0.1206x+5.8533$	$(R^2=0.9915)$
Middle region	$Y=0.0006x^2-0.1006x+4.9917$	$(R^2=0.9714)$
Lower region	$Y=0.0006x^2-0.0945x+4.4933$	$(R^2=0.9916)$

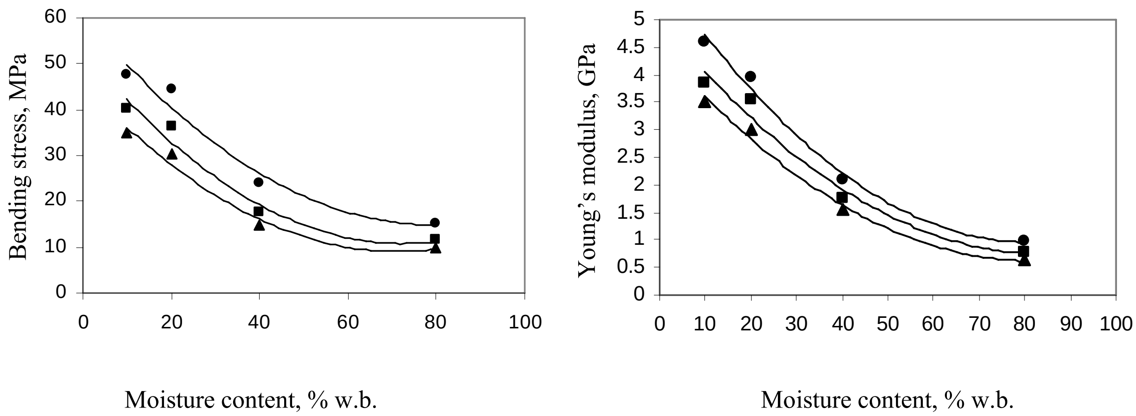

Figure 4. The changes bending stress and young's modulus with moisture content according to the regions; ▲lower region; ■ middle region; ●upper region.

3.3. Shearing Stress

Figure 5 presents an exponentially increasing relationship between the shearing stress and moisture content for all regions as reported by most previous researchers (McRandal and McNulty, 1980; Annoussamy et al., 2000). The highest shearing stress was obtained as 28.16 MPa in the lower region at a moisture content of 80%, while the lowest shearing stress was found to be 5.98 MPa in the upper region at a moisture content of 10%.The shearing stress decreased towards the upper regions of the stalk. The differences in the values for the shearing stress in the intermediate stalk regions also reduced as the moisture content decreased. This may be attributed to decreasing of the density differences between the regions at low moisture contents. Measurement of the shear strength of alfalfa stems by Halyk et al (1968) showed mean values in the range 0.4–18 MPa. They reported that a decrease in shear strength accompanied an increase in moisture content at all of the height regions. In addition, according to the Duncan's multiple range tests, the values for the shearing stress in the lower region were found to differ from those for the middle and upper regions. The relationship between moisture content and shearing stress can be expressed by the following equation:

Lower region	$Y=0.0013x^2+0.1185x+10.2150$	$(R^2=0.9798)$
Middle region	$Y=0.0024x^2-0.0190x+9.0183$	$(R^2=0.9824)$
Upper region	$Y=0.0008x^2+0.0446x+6.2383$	$(R^2=0.9320)$

3.4. Shearing Energy

The shearing energy requirement increased linearly with increases in the moisture content for all regions (Fig. 5). This effect of moisture content was also reported by Annoussamy et al. (2000) for wheat straw and by Chen et al. (2004) for hemp stalk. The values of shearing energy varied from 20.20 to 345.80 mJ in upper region had lowest moisture contents and lower region had highest moisture contents, respectively. The reason for this difference may be expressed due to the viscous damping effect of moisture as reported by Persson (1987). The shearing energy also decreased towards the upper regions. Its values varied between 20.2–73.1, 64.20–187.60, and 185.20–345.8 mJ for the upper, middle and lower regions, respectively, at the different moisture contents studied. It was greater in the lower regions because of the accumulation of more mature fibers in the stem. The values of the shearing energy were significantly affected by moisture content and height regions at the 0.05 probability level. According to the Duncan's multiple range test results, these values are different from each other for the distinct stem regions. The relationship between moisture content and shearing energy can be expressed by the following equation:

Lower region	$Y=0.0062x^2+1.7384x+167.25$	$(R^2=0.9949)$
Middle region	$Y=0.0052x^2+1.2624x+52.79$	$(R^2=0.9983)$
Upper region	$Y=0.0007x^2+0.8307x+11.017$	$(R^2=0.9976)$

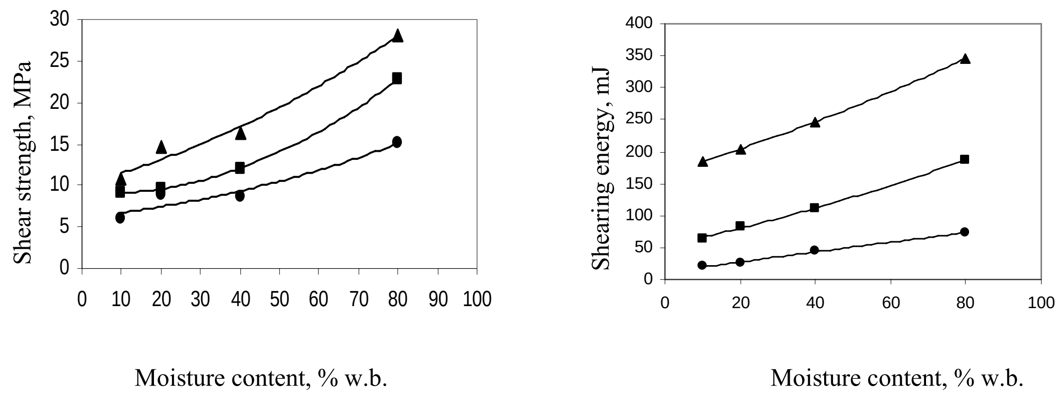

Fig. 5. The changes of shearing shear and shearing energy with moisture content according to the regions; ▲lower region; ■ middle region; ●upper region.

4. CONCLUSIONS

In this study, the effect of moisture content of alfalfa stems shear strength, shearing energy, bending stress, young's modulus was investigated according to the regions of stem. Results indicated that an increase in moisture content of stalk led to a decrease in the bending stress, young's modulus where this change led to an increase in the shearing stress and the shearing energy. The average values of the bending stress, young's modulus, and rigidity's modulus at the lowest moisture content were approximately 3 and 5 times greater than that at the highest moisture content, respectively. The shearing energy also decreased towards the upper regions. Its values varied between 20.2–73.1, 64.20–187.60, and 185.20–345.8 mJ for the upper, middle and lower regions, respectively, at the different moisture contents studied. The highest shearing stress was obtained as 28.16 MPa in the lower region at a moisture content of 80%, while the lowest shearing stress was found to be 5.98 MPa in the upper region at a moisture content of 10%.The young's modulus, bending stress, increased with towards the upper regions. The shear strength and shearing stress increased with towards the lower regions.

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