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Bending and cutting characteristics of the Cotton stalk

Ch Sravan Kumar, K.V. Prakash, Sanjeeva Reddy, Sushilendra,
P. Vijaykumar, Krishnamurty and M. Nemichandrappa

Department of Farm Machinery and Power Engineering,
College of Agricultural Engineering, University of Agricultural Sciences,
Raichur 584 104, Karnataka, India

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ABSTRACT

The bending stress, modulus of elasticity and cutting energy was measured for Cotton stalks. The bending force was measured by a cantilever beam test in field at different moistures contents and at height of 100 mm and different stalkgirths, the bending stress and modulus of elasticity was determined from these data. The cutting energy was measured by using pendulum impact tester. Maximum bending stress of 7.85 MPa was observed at 26 mm stalk girth with 10 ±5 % (w.b) moisture content. Minimum bending stress of 2.55 MPa was observed at 14 mm girth with 30±5 %(w.b) moisture content. Maximum modulus of elasticity of 40.29 MPa was observed at 26 mm girth with 10±5 % %(w.b) moisture content. Minimum modulus of elasticity of 23.14 MPa was observed at 14 mm girth with 30±5 % (w.b) moisture content. It was observed that the maximum cutting energy of 583.37 kJ were observed for 26 mm stalk girth with 10 ±5 % (w.b) moisture content and minimum cutting energy of 72.32 kJ was observed at 30 ± 5 % (w.b) moisture content (w.b) for 14 mm stalk girth. Bending stress increased as the stalk girth increased and decreased as the moisture content increased. Modulus of elasticity increased as the stalk girth increased and decreased as the stalk moisture increased. The cutting energy of cotton stalk increased as the moisture content decreased and the stalk girth increased. The velocity of cut increased as the stalk girth increased at all three moisture contents.

Key words : *Bendingstress, Cuttingenergy, Cottonstalk, Modulusofelasticity*

Introduction

Cotton (*Gossypium herbaceum*) commonly called the white gold is a soft, fluffy staple fiber which is one of the most important commercial crops playing a key role in the economic political and social affairs of India. The plant is a shrub native to tropical and subtropical regions around the world including the America, Africa and India. Millions of people lively hoods dependes on cotton crop cultivation directly or indirectly, and recent advances in cotton crop production technologies are playing an important role in the life of cotton growers. The BT cotton is extensively grown in Karnataka both in irrigated and dryland conditions. The crop production of cotton basically depends upon the inputs used, farm operations carried out and pest management practices followed. The biological material composition plays an important role in the development of any harvesting or handling machine. In a given plant species, the plant structural composition remains more or less similar contributing to its rigidity offering resistance to cutting or mechanical handling. Hence, the plant stem girth need to be considered as an important parameter to assess the bending stress, modulus of elasticity and cutting energy which play crucial role in influence the cutting force or stem failure force in shredding. Many studies have been conducted to determine the mechanical properties of plants. Ince *et el.* (2005) said that the bending stress increases as the stalk girth increases. Hoseinzadeh and Shirneshan (2012) emphasized that the moisture content of the stem increased, the bending stress decreased. Similar results were also reported by Esehaghbeygi *et al.* (2009) for wheat, Shahbazil and Galedar (2012) for safflower. Considering the above points, there is a need for information on the variation in the physico-mechanical properties of cotton stalk to improve chopping and shredding conditions. This study was focused on determining the bending stress, the modulus of elasticity in bending, and the cutting energy of cotton stalks according to various stalk regions at different moisture contents.

Materials and Methods

Physical and mechanical properties of plants and their residues are important in relate to the harvesting machines used for stalk removing (Du and Wang, 2016). The physical properties of cellular material which are important in cutting are, compression, tension, bending, density, and friction. These properties depend on spices, variety stalk diameter, maturity, moisture content and cellular structure. These physical properties are also different at different height of the plant stalk. Hence it is necessary to determine the physical and mechanical properties such as the bending and energy requirements for suitable knife design and operational parameters (Persson, 1987). The research was conducted in order to determine the bending stress, modulus of elasticity and cutting energy of cotton stalk as a function of moisture content and stalk girth.

Bending stress

The stiffness of stalk encountered during harvesting or shredding depends on the rigidity of biological material, termed as modulus of rigidity which is expressed as the product of EI, where 'E' is the modulus of elasticity in bending and 'I' is the moment of inertia of cross-sectional area of stalk. The deflection and rigidity in bending of stalk under load (force) can be determined by the cantilever test and is in relationship with 'EI' as described by theoretical equation as given below (Anand *et al*., 2015).

$$D = C \times F_b \times \frac{L^3}{EI} \quad .. (3.2)$$

Where,

D = Deflection under load in mm

C = Constant (1/3 for cantilever beam),

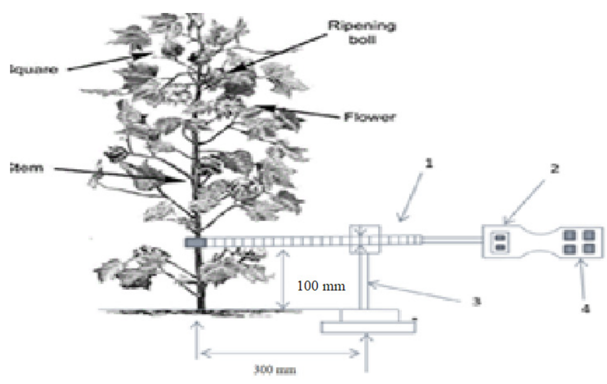
F_b = Bending force in N,

L = Length of the beam between load and support in mm,

E = Modulus of Elasticity in MPa and

I = Moment of inertia in mm^4.

In order to determine the above-mentioned parameters, the bending tests were under taken on Cotton stalks in field conditions at different moisture contents and at 100 mm heights from soil surface. The standing stalks which have different diameters were tagged in the field and the side branches and leaves which are entangling with the adjacent plant's parts are cut with sharp secateurs without causing any disturbance to the soil anchoring the plant. A flexible non elastic metallic steel tape (300 mm length) one end was tied to the plant stem (at 100 mm height from the soil surface as desired) and other end to the hook of a digital force gauge (250 N capacity and 0. 1N sensitivity).A reference stand made of heavy base plate with a 6 mm diameter rod on which a plate with indicator needle provision, whose height adjustable on the rod and can also be fixed as desired was used to measure the stalk deflection (Fig. 1). While measuring the stalk deflection, the flexible metallic tape passed through the indicator arm plate and tied to plant stem. The reference stand position was adjusted and kept such a way that the indicator needle is exactly at 300 mm position on the tape and other end of tape hooked to digital force gauge. Slowly the stalk was pulled to one side holding the digital gauge in right hand and keeping the tape parallel to soil surface. When the



1. Flexible Non elastic Scale 2. Digital Read 3. Reference rod 4. Digital Balance

Fig. 1. Bending force measurement

tape 350 mm mark reaches to indicator needle, the force recorded in the force gauge was noted down. Immediately the stalk diameter was also noted down using digital vernier calliper from the portion where the tape was tied. Knowing the stalk diameter, deflection and bending force, other parameters were worked out using the formula given above and inputting the required data in MS Excel sheet.

The bending stress experienced by the stalk at the given bending force was calculated by using the equations as given below (Ince *et al*., 2005).

$$M_b = F_b \times L \quad \text{.. (3.3)}$$

$$\sigma_b = \frac{M_b \times y}{I} \quad \text{.. (3.4)}$$

Where,

M_b = Bending Moment in N-mm,

F_b= Bending force in N

σ = Bending stress, MPa

L = Length of the beam between load and support in mm.

y = Distance of outermost fibre from the neutral axis in mm

I = Moment of inertia mm^4

Cutting Energy

The cutting action of a tool is very important process in many agricultural machinery operations such as crop harvesting, forage harvesting, weeding, stalk shredding, lawn moving etc. The single element cutting action in shredding differs greatly from that of using two opposed elements in case of cutter bar and scissoring action of other cutting devices. Cutting with single element purely occurs due to impact cutting action of the element which depends on the distance at which blade action takes place from anchoring base or support base of stalk; knife speed, cutting element sharpness and crop inertia (stem girth). So, to determine the stalk cutting energy under a single rotary element (blade) condition at different moisture conditions and girth of stalks a pendulum type impact tester was developed (Fig. 2).

The pendulum of the impact tester is suspended at its top end and has a knife fixed at lower end is made to oscillate in vertical plane. At bottom there is a sample cotton stalk fixed in the holder. To impart enough energy to cut the sample, the pendulum is normally displaced to one side of the equilibrium position by an angular deflection θ_d. By the principle of conservation of energy, the pendulum arm when

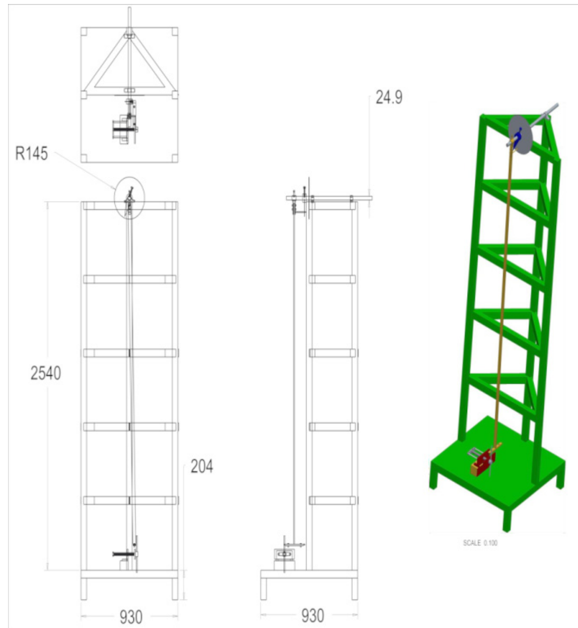


Fig. 2. Pendulum impact tester

released is expected to oscillate to other side of equilibrium line and deflect through an angle θc, which is normally less than θ_d due to frictional resistance in the parts and air resistance. In the pendulum operation process, there is continuous exchange of energy of the swinging arm from maximum potential energy when the arm is at its extreme position before it is released to swing down gaining kinetic energy to maximum kinetic energy when the arm is at equilibrium line at the cost of potential energy loss.

In these processes the cutting energy exerted by the blade and its cutting velocity are determined by using the following respective formulae (Prasad and Gupta, 1975).

$$E = W \times R(\cos\theta_c - \cos\theta_d) \quad \text{.. (3.5)}$$

Where,

W = Total Weight of pendulum arm in Newton.

E= cutting energy in J

R = Centre of gravity with respect to rotation of pendulum arm in m

θ_c = Pendulum angle after cutting

$\theta_{d=}$ pendulum angle before cutting

Blade velocity

$$V_c = \frac{\sqrt{2WR(1 - \cos\theta_d)}}{I} \quad \text{.. (3.6)}$$

Where,

$V_{c=}$ Cutting velocity, ms^{-1}
L = Length of pendulum in m
I= Moment of inertia of pendulum in kg m^{-2}

Results and Discussion

Effect of different cotton stalk girth and moisture contents on bending stress (MPa)

The procedure adopted to measure the modulus of elasticity at different moisture contents of cotton stalk after physiological maturity is explained in material and methodology. The bending stress was measured at 100 mm height from soil surface and at different stalk girths (14, 16, 18, 20, 22, 24, and 26 mm), and moisture contents (30±5%, 20±5% and 10±5% w.b.) are presented in Table 1.

Table 1. Bending stress at different stalk girths and moisture levels

Stalkgirth, mm	Bending stress MPa		
	Moisture (%, w.b)		
	10 ±5	20 ±5	30 ±5
14	3.29	2.86	2.55
16	4.01	3.35	3.23
18	4.85	3.86	3.88
20	5.19	4.38	4.44
22	6.20	5.23	5.06
24	6.98	5.94	5.83
26	7.85	7.03	6.82

It was observed that, the bending stress of cotton stalk varied from 2.55 to 7.85 MPa (Table 5) at different moisture contents and stalk girths. A maximum bending stress of 7.85 MPa was recorded at 26 mm stalk girth with 10 ±5 % moisture content and minimum (2.55) at 14 mm girth with 30±5 % moisture content. The individual and combined effects of stalk girth, and moisture content on bending stress were analyzed statistically and are presented in Table 2. The statistical analysis shows that, the stalk girth (G) and moisture content (M), individually are significantly influenced the bending stress at 1 % level of significance. The interaction effect of moisture content and stalk girth (M X G) are not significant. The effect of stalk girth, moisture content on bending stress have been plotted in Fig. 3. From figure, it was inferred that the bending stress increased as the stalk girth increased and decreased as the stalk moisture content increased. The decrease in bending stress indicates a reduction in the brittleness of stalk and also as the girth increased, the bending stress increased due to stiffness of the stalk. The similar findings were reported by Ince *et al*. (2005) for sunflower stalk residue, Shahbazi and Nazari (2012) for safflower stalk and Ananda *et al*. (2015) for maize stalk.

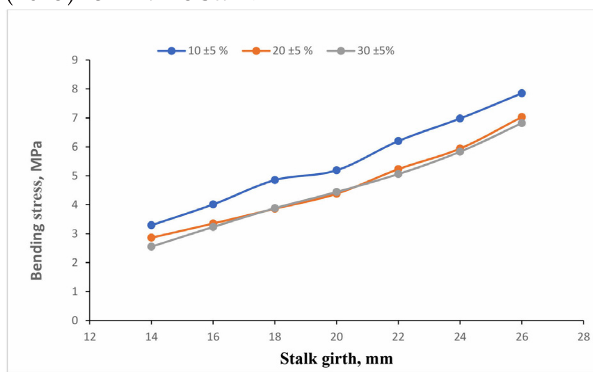


Fig. 3. Effect of stalk girth (mm) and moisture content (%) on bending stress

Effect of different cotton stalk girth and moisture contents on modulus of elasticity

The Modulus of elasticity was measured at 100 mm height from soil surface and at different stalk girths (14, 16, 18, 20, 22, 24, and 26 mm), and moisture contents (30±5%, 20±5% and 10±5% w.b.) are presented in Table 3. It was observed that, the modulus of elasticity of cotton stalk varied from 23.14 to 40.29 MPa at different moisture contents and stalk girths. A maximum modulus of elasticity of 40.29 MPa was recorded at 26 mm stalk girth with 10±5 % moisture content and minimum of 23.14 MP at 14 mm girth

Table 2. Analysis of variance of bending stress for different moisture contents

Source	SS	DF	MS	Fvalue	Prob>F	
Model	133.10	20	6.65	21.52	< 0.0001 *	**Significant**
Moisture content (M)	7.76	2	3.88	12.55	< 0.0001 *	
Stalk girth (G)	123.05	6	20.50	66.34	< 0.0001*	
M x G	2.28	12	0.19	0.61	0.81NS	
Pure Error	12.98	42	0.30			
Cor Total	146.09	62				

Table 3. Modulus of Elasticity at different stalk girths and moisture levels

Stalkgirth, mm	Modulus of Elasticity MPa		
	Moisture (%, w.b)		
	10 ± 5	20 ± 5	30 ± 5
14	29.80	25.69	23.14
16	31.61	26.74	25.84
18	34.25	27.28	27.54
20	33.57	28.01	29.37
22	36.35	30.93	29.62
24	38.46	32.08	32.09
26	40.29	34.91	34.11

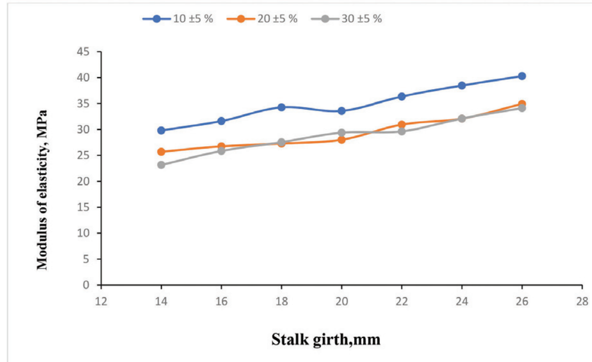


Fig. 4. Effect of stalk girth (mm) and moisture content (%) on modulus of elasticity

with 30±5 % moisture content.

The individual and combined effects of stalk girth and moisture content on modulus of elasticity were analyzed statistically and presented in Table 4. The statistical analysis shows that, the moisture content (M),) and stalk girth (G), significantly influenced modulus of elasticity at 1 % level of significance. The interaction effect of moisture content and stalk girth (M X G) are not significant.

The effect of stalk girth and moisture content on modulus of elasticity have been presented in Fig. 4. From the figure, it was inferred that the modulus of elasticity increased as the stalk girth increased and decreased as the stalk moisture increased. This indicates that, there is a difference in physical and biological properties of cotton stalk due to difference in maturity level. Similar trend was reported by Ince *et al*. (2005) for sunflower stalk residue; Amer *et al.* (2008) for cotton stalk; Ananda *et al*. (2015) for maize stalk; Vivek *et al.* (2015) for cotton stalk.

Effect of different cotton stalk girths and moisture contents on cutting energy(kJ)

The cutting energy was determined by the procedure explained under 3.1.2.2. In this particular aspect two experiments were carried out to identify blade velocity and cutting energy. The cutting energy and velocity of cotton stalk at different blade velocities was measured by using the equations 3.12 and 3.13. The cutting energy was studied at different stalk girths (14, 16, 18, 20, 22, 24 and 26 mm) and moisture contents (30 ±5, 20 ±5 and 10 ±5) and are presented in Table 5.

It was observed that, the cutting energy for cotton stalk varied from 72.329 to 583.372 kJ at different moisture contents and stalk girths. In the present study higher cutting energy cutting energy of 583.372 kJ was recorded at 26 mm stalk girth with 10±5 % moisture content and minimum cutting energy of 72.329 kJ at 14 mm girth with 3 0±5 % moisture content.

Table 5. Cutting energy kJ at different stalk girths and moisture level

Stalkgirth, mm	Cutting energy, kJ		
	Moisture (%, w.b)		
	10 ±5	20 ±5	30 ±5
14	254.87	140.60	72.32
16	320.33	229.32	161.98
18	353.43	310.67	236.27
20	401.60	345.74	252.68
22	428.84	367.43	301.96
24	451.91	389.53	326.22
26	583.37	450.60	377.05

Table 4. Analysis of variance of modulus of elasticity for different moisture contents

Source	SS	DF	MS	Fvalue	Prob>F	
Model	1072.99	20	53.64	3.34	<0.0005*	**Significant**
Moisture content (M)	303.89	2	151.94	9.48	<0.0004*	
Stalk girth (G)	648.68	6	108.11	6.74	<0.0001*	
M x G	120.40	12	10.03	0.62	0.80 NS	
Pure Error	672.90	42	16.02			
Cor Total	1745.89	62				

The individual and combined effects of stalk girth and moisture content on cutting energy were analyzed statistically and presented in Table 6. The statistical analysis shows that, the moisture content (M) and stalk girth (G) variables significantly influenced on cutting energy at 1 % level of significance. The interaction effect of moisture content and stalk girth (M X G) are not significant. The effect of stalk girth and moisture content on cutting energy have been presented in Fig 5. It was inferred that, cutting energy increased as the stalk girth increased and moisture content decreased.

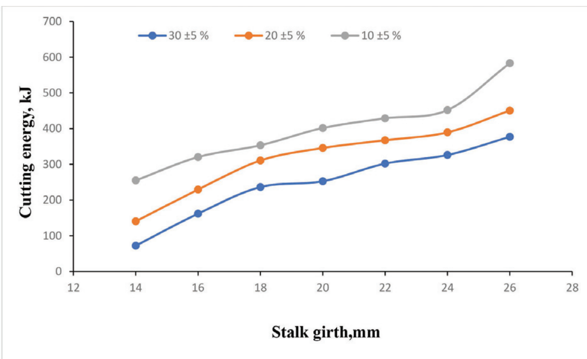


Fig. 5. Effect of stalk girth (mm) and moisture content (%) on cutting energy

The effect of stalk girth and moisture content on cutting energy have been presented in Fig 5. It was inferred that, cutting energy increased as the moisture content decreased and increased as the stalk girth increased. The results are in consonance with the results reported by Atul *et al*. (2011) for Pigeon pea stalks; Azadbakht *et al*. (2014) for corn stalk.

Effect of different cotton stalk girth and moisture contents on cutting velocity (ms^{-1})

The velocity of cut of cotton stalk was determined by following the procedure explained under 3.3.2.2. The velocity of cut were studied at different stalk girths (14, 16, 18, 20, 22, 24 and 26 mm) and moisture contents (30 ±5, 20 ±5 and 10 ±5). The effect of stalk girth and moisture content on velocity of cut is presented in Table 7. It was observed that, the velocity of cut for cotton stalk varied from 2.56 to5.8 ms^{-1} at different moisture contents and stalk girths.

Table 7. Velocity of cut ms^{-1} at different stalk girths and moisture levels

Stalkgirth, mm	Velocity, ms^{-1} Moisture (%, w.b) 10 ±5	20 ±5	30 ±5
14	3.09	2.83	2.56
16	3.35	3.35	3.09
18	3.93	3.83	3.35
20	4.3	4.19	3.95
22	4.3	4.3	4.1
24	4.73	4.73	4.52
26	5.8	5.72	5.65

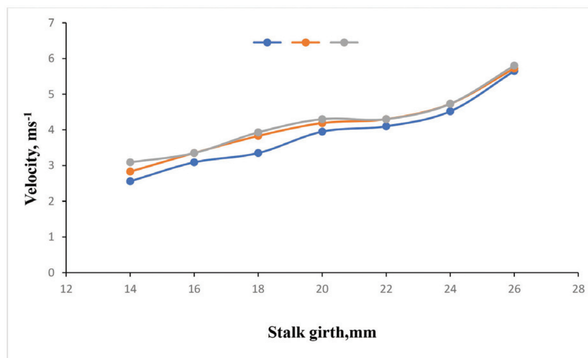


Fig. 6. Effect of stalk girth (mm) and moisture content (%) on velocity ms^{-1}

The individual and combined effects of stalk girth and moisture content on velocity of cut were analyzed statistically and presented in Table 8. The statistical analysis shows that, the moisture content (M) and stalk girth (G) variables individually and the interaction effect of moisture content and stalk girth (M X G), are significantly influenced on velocity of cut at 1 % level of significance.

Table 6. Analysis of variance of cutting energy for different moisture contents

Source	SS	DF	MS	F value	Prob > F	
Model	832006.6	20	41600.33	10.30561	< 0.0001	**Significant**
Moisture content (M)	243651.3	2	121825.7	30.17977	< 0.0001	
Stalk girth (G)	574573.2	6	95762.19	23.72309	< 0.0001	
M x G	13782.12	12	1148.51	0.284519	0.98NS	
Pure Error	169540	42	4036.667			
Cor Total	1001547	62				

Table 8. Analysis of variance of velocity of cut for different moisture contents

Source	SS	DF	MS	F value	Prob > F	
Model	51.75877	20	2.587938	189.2514	< 0.0001*	Significant
Moisture content(M)	1.548994	2	0.774497	56.63761	< 0.0001*	
Stalk girth (G)	49.80912	6	8.30152	607.0758	< 0.0001*	
M x G	0.400651	12	0.033388	2.441575	0.01NS	
Pure Error	0.574333	42	0.013675			
Cor Total	52.3331	62				

The effect of stalk girth and moisture content on velocity of cut have been presented in Fig. 6. It was inferred that, velocity of cut increased as the stalk girth increased at all three moisture contents. These results are in close agreement with the research findings of Yiljep and Mohammed (2005) for sorghum stalk and Ananda *et al*. (2015) for maize stalk.

Conclusion

The bending stress, modulus of elasticity and cutting energy was measured for Cotton stalks in order to determine the optimum moisture content to harvest the cotton stalk. The cutting energy of cotton stalk increased as the moisture content decreased and the stalk girth increased. The cutting energy of cotton stalk increased as the moisture content decreased and the stalk girth increased.

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