Modeling shear resistance of alfalfa stem against semi-static loads

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Abstract: Knowledge of the physical properties of alfalfa stems is essential in the design of alfalfa harvesting machines. In this research, the components of force, strength, energy, and shearing power in fresh alfalfa stem by cutting blade at four-speed levels of V_1=125 mm min^{-1}, V_2=250 mm min^{-1}, V_3=375 mm min^{-1}, V_4=500 mm min^{-1} and three ranges of diameter D_1=2-2.5 mm, D_2 =2.5-3 mm, D_3=3-3.5mm has been investigated. Examining Duncan's variance analysis table shows that the changes in speed and diameter on the force, stress, energy, and shear power are significant at a 1% level. The range of force, tension, energy, and shear power is 1.72-37.57 N, 0.47-4.64 Mpa, 0.008-0.15 J, and 0.004-0.086 W, respectively. Also, to investigate the cumulative effect of cutting the stems that occurs in harvesting with a cutting comb, the components of force, energy, and shearing power have been investigated in bunches of two, three, and four hay at a speed level of 500 mm min^{-1}. The range of force, energy, and shear power in the multiple of alfalfa stem are 11.16-49.06 N, 0.07-0.46 J, and 0.04-0.18 W, respectively.

Keywords: alfalfa stem, shear strength, shear force, loading rate

Citation: Roshanghiyasi, H., A. Jafari, and H. Z. Dizaji. 2025. Modeling shear resistance of alfalfa stem against semi-static loads. Agricultural Engineering International: CIGR Journal, 27(1):176-187.

1 Introduction

Alfalfa is one of the most essential types of animal fodder in Iran, which is an excellent source of protein, vitamins, and minerals. Information about power, energy, and shearing power can help a lot in the design of harvester machines. Research in the field of properties of agricultural products is generally included in two categories: a) application of basic principles of mechanics in the biological behavior of products and b) adaptation of laboratory methods developed for non-biological materials (Nazari Galedar et al., 2008). The shearing physical properties of the cellular material depend on the species, variety, stem diameter, maturity, moisture content, and cellular structure (Nazari Galedar et al., 2009), Studies have been done on the physical and mechanical properties of the stems of agricultural products them, the effects of various parameters such as humidity change, diameter change, cutting location, etc. the physical and mechanical properties have been discussed and investigated.

Halyk and Hurlbut (1968) investigated the effect of moisture on the tensile strength of alfalfa stems, and they found that the tensile strength of alfalfa stems is between 9 and 36 Map this range has a negative linear correlation with moisture content.

Taghinezhad et al. (2013) Investigated the effect of moisture on shear energy in alfalfa stems. They found out the mean specific cutting energies of cane

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Received date: 2024-02-29 **Accepted date:** 2024-12-11

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stems at low, medium, and high levels of moisture content were 34.071, 28.339, and 16.297 kN m^{-1}. Tavakoli et al. (2009) investigated the effect of moisture content and loading speed on the cutting factors of barley straw. They found that the increase in cutting speed and the shearing force of straw change with each other. Zhang et al. (2014) investigated the shear mechanical properties of alfalfa stems. Their research shows that stem cutting is divided into three mechanical stages: tensile, tensile and shear, and pure shear. The change process of mechanical parameters such as mechanical parameters of materials and mechanical parameters of the structure are different, and the influencing factors of low and middle alfalfa stem shear stress are different. Azadbakht et al. (2016) investigated the shearing mechanical components of canola stems with cutting blades of three diameters and three cutting surfaces. Their investigations show that the increase in the diameter of the cutting components, including force, energy, and power has increased, and with the increase in the cutting speed of the cutting components, it has decreased. Kamandar and Massah (2017) investigated the effect of speed on the shear force of canola stalks. Their research shows that the shear force and energy decrease significantly with increasing speed at 0.01%.

Ahmad et al. (2015) investigated the components of cutting mechanics in wheat straw, their studies show that the position between the nodes and the speed of loading on the mechanical components are significant at the 5% level. Kamandar et al. (2018) investigated the static and dynamic shear force of privet stem. Their investigation shows that the dynamic force is far less than the static force, and the shear energy decreases with increasing speed. Yiljep and Mohammed (2005) investigated the effect of impact speed on the cutting energy of sorghum stem, their studies show that changing the speed is effective in changing the shear energy of sorghum stem. The maximum cutting efficiency is 98% and 97%, respectively, at knife speeds of 5.2 and 7.3 m s^{-1}. Iwaasa et al. (1995) investigated the shearing force of alfalfa in different cultivars. The results of their investigation show that the shearing force in different cultivars is different compared to each other Also there is a positive correlation between shearing force and stem diameter.

Chen et al. (2004) found that the average values of the maximum force and the total cutting energy for hemp were 243 N and 2.1 J, respectively. Zhang et al. (2016) investigated the mechanical properties of different parts of the tomato stem, and their investigation shows that the mechanical components decrease with distance from the lower part of the stem. Dauda et al. (2015) investigated the effect of speed on the shear components of kenaf stalks. They examined the stalks in several diameter groups with several moisture levels at four rotational levels of 400, 500, 600, and 700 rpm. Their results showed that increasing the speed from 400 to 700 rpm decreased the cutting torque from 1.91 N m to 1.49 N m.

Song et al. (2022) studied the effect of cutting parameters on the ultimate shear stress and specific energy of sisal leaf cutting. Their investigation shows that cutting speed, blade angle, blade entry angle, and leaf height from the ground significantly affect the final shear stress and specific energy of sisal leaf cutting. The values of optimal cutting parameters, i.e. cutting speed, blade inclination angle, blade entry angle, and blade elevation angle, obtained by solving the multi-objective response equation are 500 mm min^{-1}, 24.23°, -28.8°, and 20°, respectively. Under these settings, the ultimate shear stress and specific shear energy for sisal leaf can be reduced by 43.48% and 10.71%, respectively, compared to the case close to practical harvesting.

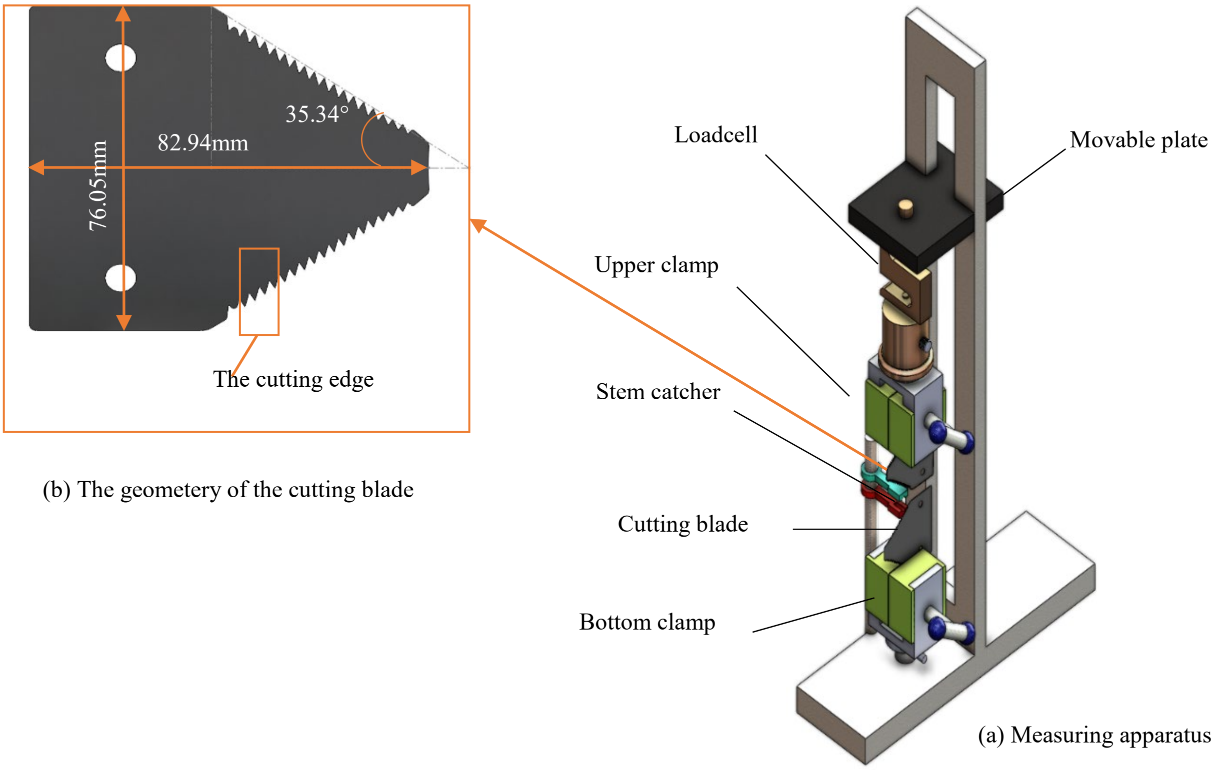
In this research, to extract the components of force, energy, and cutting power necessary for harvesting fresh hay with a practical approach to be used in hay harvesting operations by harvesters with a shearing comb mechanism, the effect of stem diameter and cutting speed in the cutting process has been investigated. Also, the cumulative effect of cutting the stems on the cutting components, which sometimes occurs in the blades at high densities of the product, has been investigated and compared with the theoretical values.

2 Material and methods

To investigate the shear force components of fresh alfalfa stalks (Medicago sativa L. Hamdani cv), the stalk samples were collected randomly from a two-hectare field at the time of its harvest. The stems were cut from the zero point of the ground before sunrise, and immediately after cutting, to prevent moisture loss, the stems were placed in a special bag and transported to the agricultural products properties laboratory located on the agricultural campus of the University of Tehran. Considering that the harvesting operation is done at the lowest possible part, therefore, all the experiments were done at a distance of 0-5 cm from the stems.

2.1 Single stem

According to the wide diameter of harvested alfalfa stems, to check them more closely, the stems were classified into three categories with diameters D_1, D_2, D_3, and their cutting components with the mechanism shown in Figure 1 using the test device tension/compression testing machine (Instron Universal Testing Machine/SMT-5, SANTAM Company, Tehran, Iran). The test machine, equipped with a 20 kg load cell, was extracted by a blade for harvesting hay with a sharpness of 35.34° Figure 1b at four-speed levels V_1, V_2, V_3, and V_4 in 20 repetitions according to Table 1. The cutting components, graphs, and equations governing the changes in each process were extracted (Nazari Galedar et al., 2008).



(b) The geometery of the cutting blade

(a) Measuring apparatus

Figure 1 Schematic of the apparatus for the measurement of the shear force and extension (a) (b)

Table 1 Test treatments included stem diameters and cutting speed levels

Diameters(D)	Cutting speed levels (V)			
	V1=125mm/min	V2=250mm/min	V3=375mm/min	**V4=500mm/min**
D_1=2-2.5mm	D_1V_1	D_1V_2	D_1V_3	**D_1V_4**
D_2=2.5-3mm	D_2V_1	D_2V_2	D_2V_3	**D_2V_4**
D_3=3-3.5mm	D_3V_1	D_3V_2	D_3V_3	**D_3V_4**

2.1.1 Shear force

The force required to cut the stem, represented by the maximum value noted in the force-displacement diagram, was measured using the tension-compression test device as shown in Figure 2.

2.1.2 Shear strength

By dividing the maximum shear force by the surface of the cut stem (Figure 2), the shear resistance of each stem is calculated according to Equation 1. The cross-section area of stem (A) determined by having the stem diameter (D_i).

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

2.1.3 Shear energy

By using the integration of the force-displacement diagram (Figure 2), according to Equation 2, the energy required to cut each alfalfa stem was calculated (Nazari Galedar et al., 2009).

$$E_S = \int_0^l F_s dx \qquad (2)$$

2.1.4 Shear Power

By dividing the shearing energy required to cut each stem (Es) by the cutting time of the stem according to Equation 4, the shearing power required to cut alfalfa stems has been calculated.

$$T = \frac{L_s}{V_i} \qquad (3)$$

$$P_S = \frac{E_S}{T} \qquad (4)$$

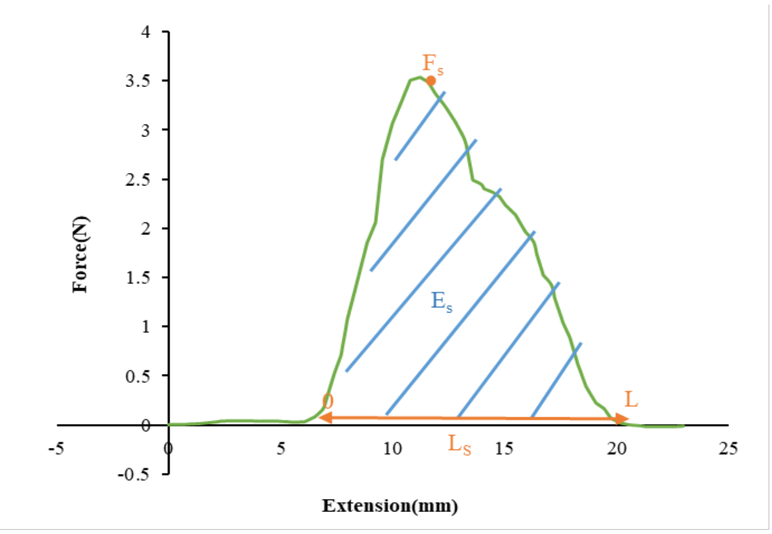


Figure 2 The force-displacement diagram of stem cutting

2.2 Multiple stems

In the investigation of the effect of multiple cutting, which sometimes happens in the cutting operation by a harvester machine, 20 groups of four hay were randomly determined from the prepared sample. The stems were cut in single, double, triple, and quadruple bundles according to the pattern shown in Figure 3 at the speed of 500 mm/min so that each stem was cut individually at first and then investigated the effect of multiples in cutting the mentioned bunches with other stems at the same time. According to formulas 2, 1, and 3, the parameters in question were calculated, and then the practical values obtained from the SANTAM device were compared with the theoretical values.

2.3 Statistical analysis

The study was planned as a completely randomized block design with 20 replicates in each treatment. Experimental data were analyzed using the analysis of variance (ANOVA) and, the means were separated at the 1% level by applying Duncan's multiple range test in SPSS software (version. 23, SPSS, Inc., Chicago, IL, USA).

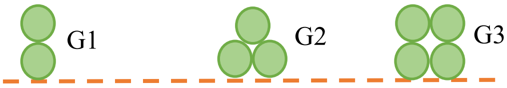


Figure 3 Multiple groups of alfalfa stems for cutting pattern

3 Results and discussion

3.1 Single stem

Average values for physical and mechanical properties are shown in Tables 2 and 3. The effects of stem diameter on Shear Force, Shear strength, Shear Energy, and Shear Power were significant at 1%. The effects of cut speed on Shear Force, Shear strength, Shear Energy, and Shear Power were significant at 1%. The interaction of stem diameter and cutting speed on the shear force, shear strength, and shear power were significant at 5%, while the effect on shear stress was insignificant. An example of shear force-displacement diagrams in a single stem shear test is shown in Figure 4. The results obtained are discussed in detail below.

Table 2 Mean values for the physical properties of samples

	Diameter levels		
Diameter (mm)	D_1	D_2	D_3
	2.195	2.718	3.145
Area (mm^2)	3.7972	5.8062	7.8163

Table 3 Mean values of the mechanical properties of single-stem cutting

	D_1				D_2				D_3			
	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4	V_1	V_2	V_3	V_4
F_s(N)	9.95	8.26	6.14	4.82	14.40	10.69	7.91	7.03	23.91	17.17	15.22	14.13
τ_s(Mpa)	2.68	2.18	1.62	1.27	2.49	1.84	1.37	1.21	3.08	2.21	1.96	1.82
E_s(J)	0.033	0.032	0.027	0.027	0.058	0.049	0.042	0.043	0.107	0.091	0.09	0.093
P_s(W)	0.008	0.013	0.015	0.016	0.012	0.018	0.022	0.028	0.021	0.032	0.044	0.056
L_s(mm)	8.52	10.66	11.42	14.62	10.08	11.53	12.39	13.57	10.49	12	12.65	13.87

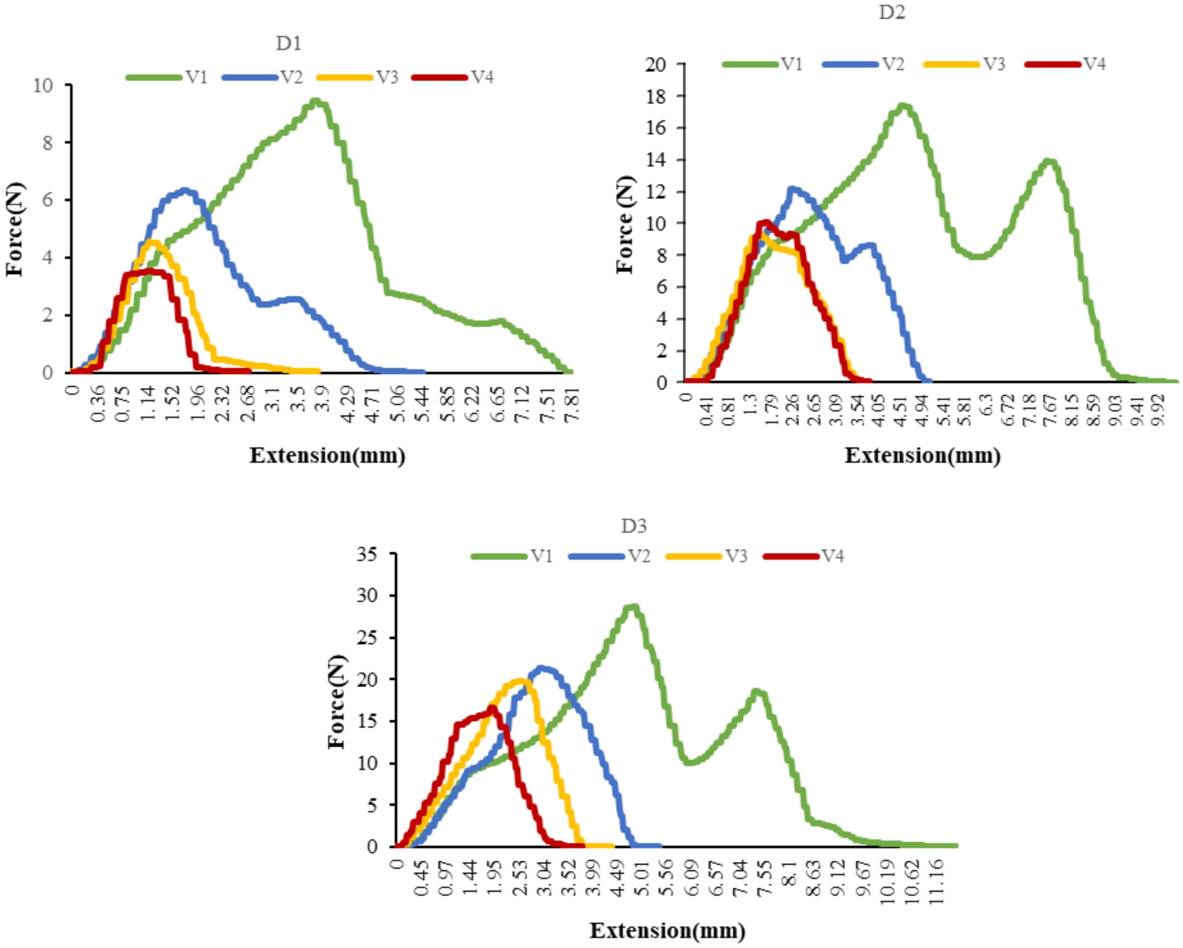


Figure 4 The shear force-displacement graphs for the single stem cutting test across three different diameters (D1, D2, D3)

3.1.1 Shear force

Figure 5 shows the exponentially decreasing relationship between cutting speed for all diameters. Between the treatments, the maximum shear force value recorded was 37.57N at D3 with V1 cut speed, while the minimum value was 1.72N at D1 with V4 cut speed. The shear force decreased toward increased cut speed, so that in agreement with previous research (Tavakoli et al., 2009). The equations delineating the relationship between shear force and cutting speed for each classified stem, accompanied by their respective coefficients of determination (R^2), are detailed in Table 4.

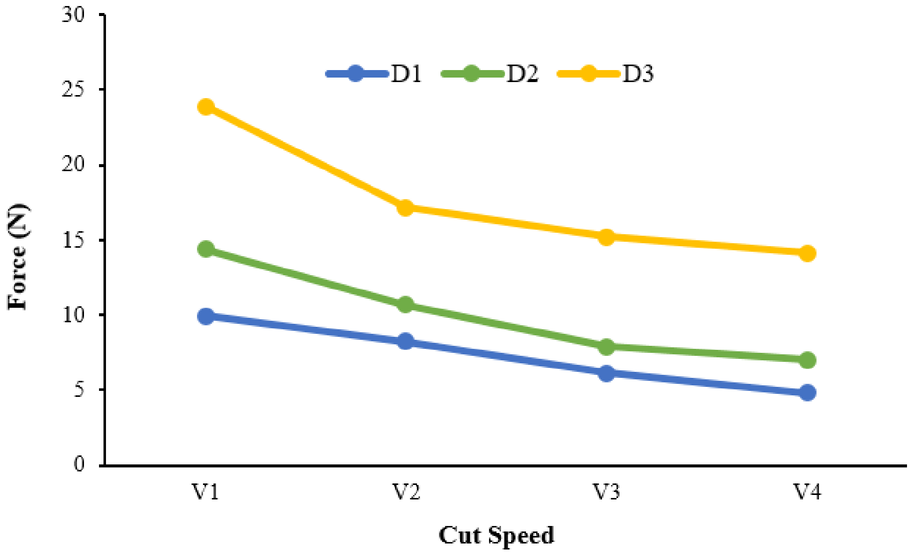


Figure 5 Effect of cutting speed and stem diameter on shear force in single stem cutting test

Table 4 Equations representing the relationship between the mechanical properties of alfalfa stem and cutting speed content for each stem diameter class

	D_1	R^2	D_2	R^2	D_3	R^2
F_s(N)	$F_S = 0.0993\ V_i^2 - 2.2479\ V_i + 12.16$	0.9956	$F_S = 0.7068\ V_i^2 - 6.0226\ V_i + 19.76$	0.9986	$F_S = 1.4136V_i^2 - 10.196\ V_i + 32.498$	0.9864
τ_s(Mpa)	$\tau_s = -0.951\ln(V_i) + 2.4818$	0.9922	$\tau_s = 3.5116e^{-0.254V_i}$	0.9947	$\tau_s = 3.0118V_i^{-0.382}$	0.982
E_s(J)	$E_s = 0.0362e^{-0.082V_i}$	0.897	$E_s = 0.0024\ V_i^2 - 0.017\ V_i + 0.0725$	0.9927	$E_s = 0.0047\ V_i^2 - 0.0279\ V_i + 0.1295$	0.982
P_s(W)	$P_s = 0.0056\ln(V_i) + 0.0085$	0.9823	$P_s = 0.0048\ V_i + 0.0076$	0.9934	$P_s = 0.0117V_i + 0.0092$	0.9992

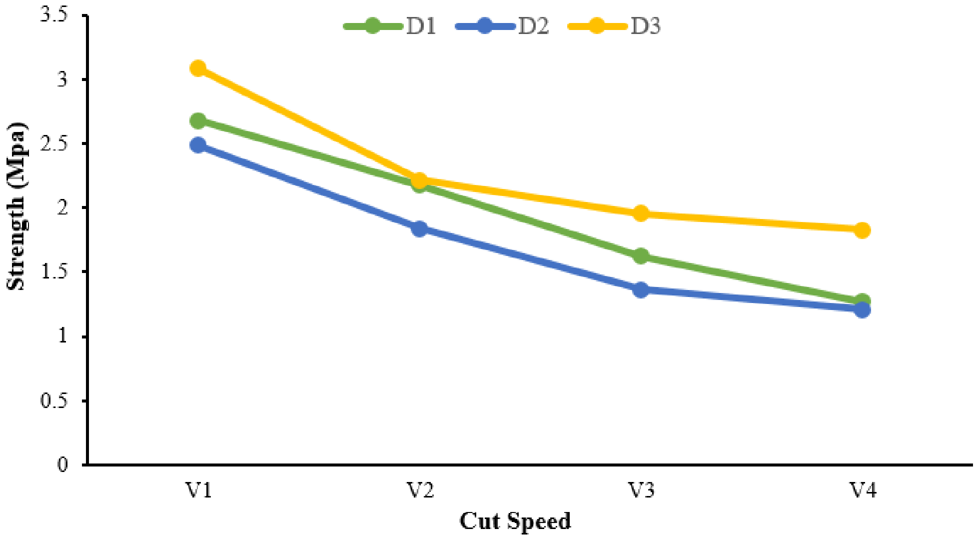


Figure 6 Relationship between the shear strength and cutting speed for the single stem diameters

3.1.2 Shear strength

According to the information presented in Figure 6 and detailed in Table 4, a notable observation was made of a decreasing exponential relationship between shear strength and cutting speed, which aligns with the findings of Nazari Galedar et al. 2009.

This pattern was consistently observed across all classes of diagonal stems analyzed in the study. Overall, among the treatments, the maximum shear strength achieved was 4.64 MPa at D3 with V1 cutting speed, while the minimum shear strength was 0.47 MPa at D1 with V4.

3.1.3 Shear energy

Based on Table 4 and Fig.7 there is an exponentially decreasing relationship between the shear energy and cutting speed for all diameter stem classes. As shown in Fig.7, the cutting energy decreased with the increase in the cutting speed of the stems. Due to the difference in the type of test, these research findings are in agreement with the findings of Yiljep and Mohammed, 2005 but not completely.

3.1.3 Shear power

An exponentially increasing relationship was observed between the shear power and cutting speed for all diameter stem classes (figure 8 and table 4). The Maximum shear power obtained was 0.086w at the D_3 with V_4 cut speed, while the lowest shear power was 0.004w at the D_1 with V_1. The shear power decreased with an increase in ctting speed.

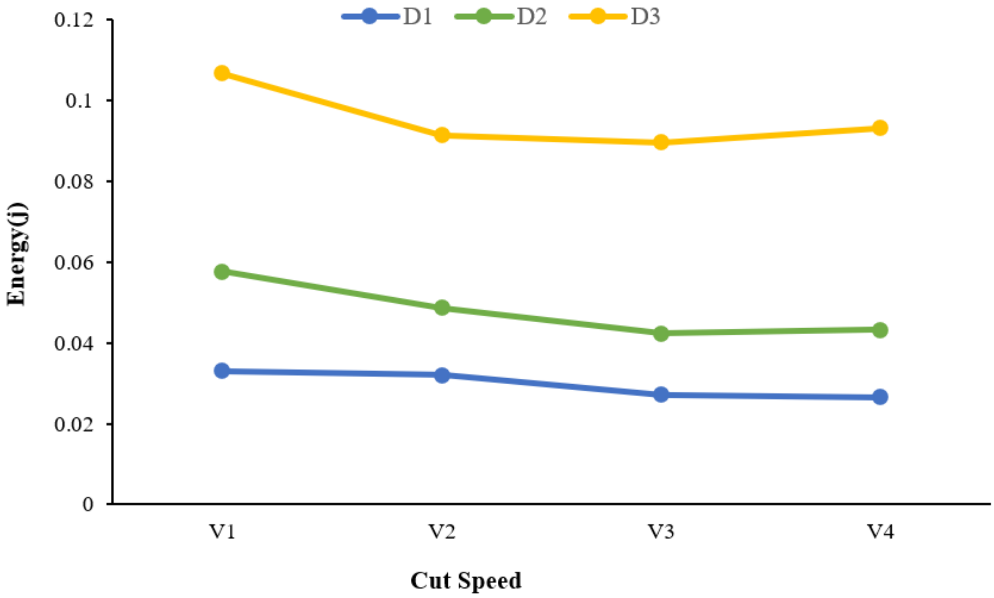


Figure 7 Shear Energy-Speed diagram of the single stem in three category diameters

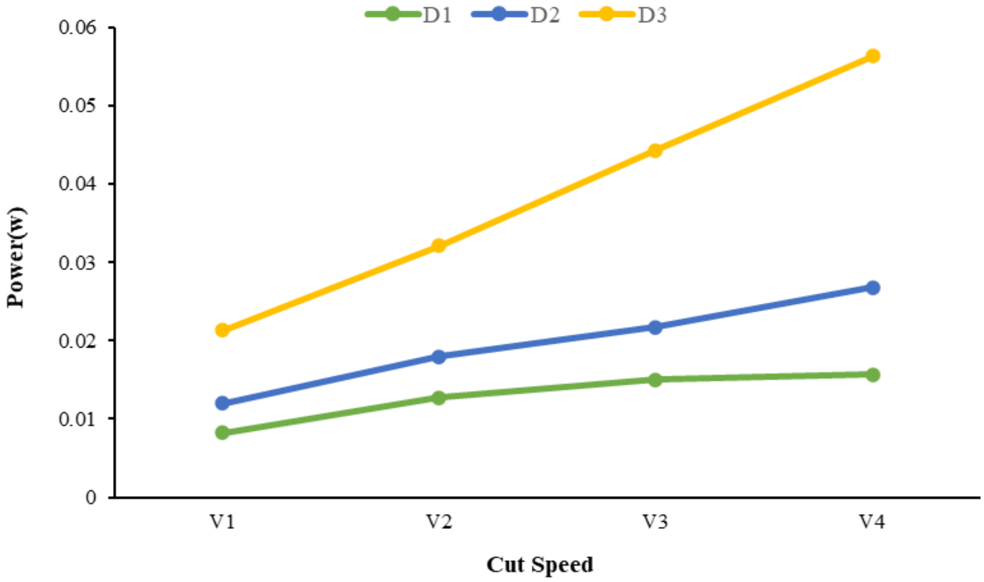


Figure 8 Shear Power -cutting speed diagram of single stem in three dimeters

3.2 Multiple stems

An example of cutting hay bunches G_1, G_2, and G_3 are shown in Figure 9. Also the average values of force, energy, and, power needed to cut each group of stems are given in Table 5. Examining the results and comparing them with the theoretical values (the theoretical value includes the sum of the mechanical components of each stem separately from each other in categories G_1, G_2, and G_3) shows that the mechanical components of practical cutting in category G_1 are less/equal and in category G_2 and G_3 are always lower.

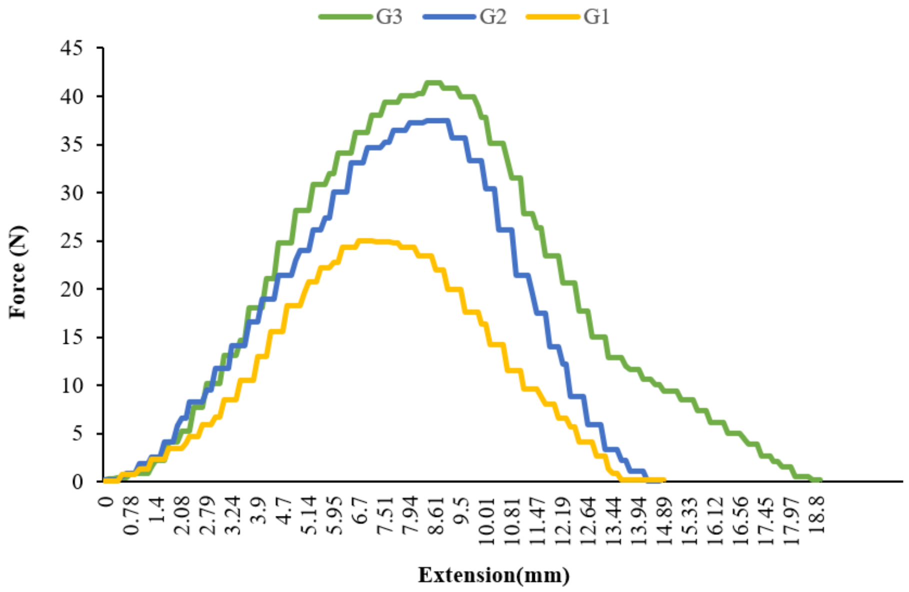


Figure 9 Shear Force-displacement diagram for multiple cutting patterns of alfalfa stems

Table 5 Mean values for the mechanical properties of multiple cutting

		G1			G2			G3	
	F(N)	E(j)	P(w)	F(N)	E(j)	P(w)	F(N)	E(j)	P(w)
Theory	23.015	0.138	0.091	34.107	0.199	0.133	45.621	0.268	0.180
Reality	23.211	0.150	0.085	28.714	0.214	0.109	33.932	0.291	0.121

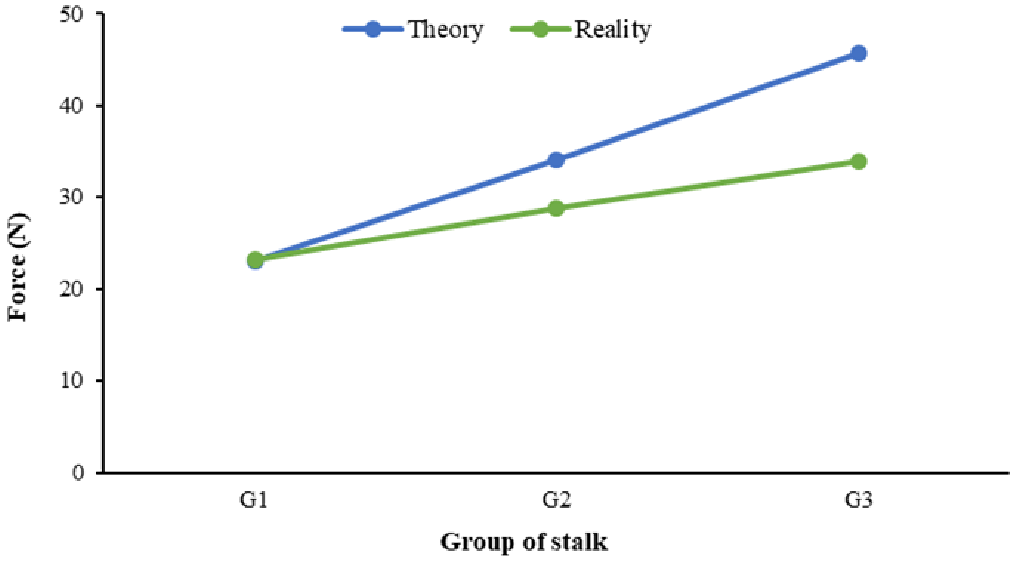


Figure 10 The relationship between shear force and the number of stems of the group in the sheared stems test

3.2.1 Multiple stem shear force

Figure 10 shows the exponentially increasing relationship between the shear force and the number of stems for all group cutting stems. The highest shear force obtained was 49.05 N at the G_3, while the lowest shear force was 11.16 N at the G_1. The shear force increased with the increasing number of cutting of the stem. By comparing the practical and theoretical values of the shearing force required to cut stems, it was observed that the practical value is a little lower than the theoretical value In G_1 while in G_2 and G_3, respectively, the practical shear force is 84.18% and 74.37% is theoretical force. Maybe the reason for this is the presence of force on the inner wall of the stems that are in contact with each other.3.2.2 Multiple stem shear energy

Figure 11 shows a linear correlation between shear energy and the number of stems in each group. The highest shear energy obtained in G3 was 0.464 J, while the lowest shear energy in G1 was 0.068 J. By comparing the practical and theoretical values of the shear energy required to cut the stems, it was observed that the practical value is higher than the theoretical values. In G1, G2, and G3, respectively, the theoretical cutting energy is 0.92%, 92.99%, and 91.78% of the practical energy.

3.2.3 Multiple stem shear power

Figure12 shows an increasing relationship between the shearing power and the number of stems in all groups, in other words, with the increase in the number of stems, the necessary shearing power also increases. The highest shear power obtained in G3 was 0.177 W, while the lowest shear power in G1 was 0.039 W. By comparing the practical, and theoretical values of the cutting force required to cut the stems of each group, it was observed that the practical value is always lower than the theoretical values. In G1, G2, and G3, the practical cutting power is 93.4%, 81.9%, and 67.2% of the theoretical power, respectively.

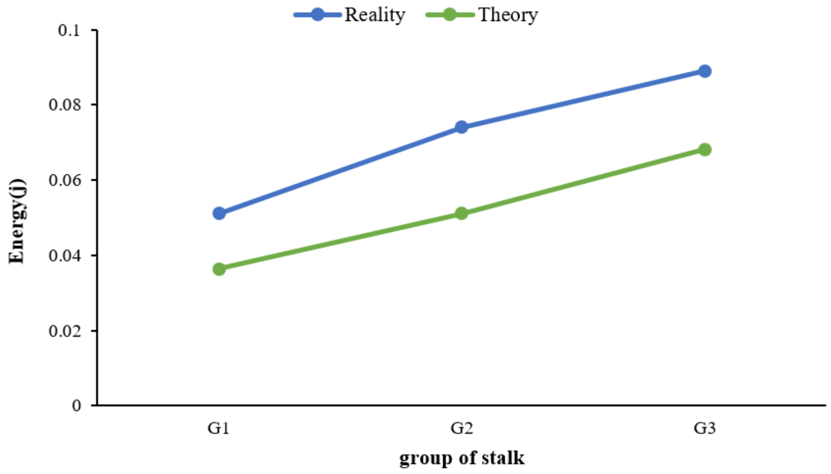


Figure 11 Practical and theoretical shear energy in the stem number category

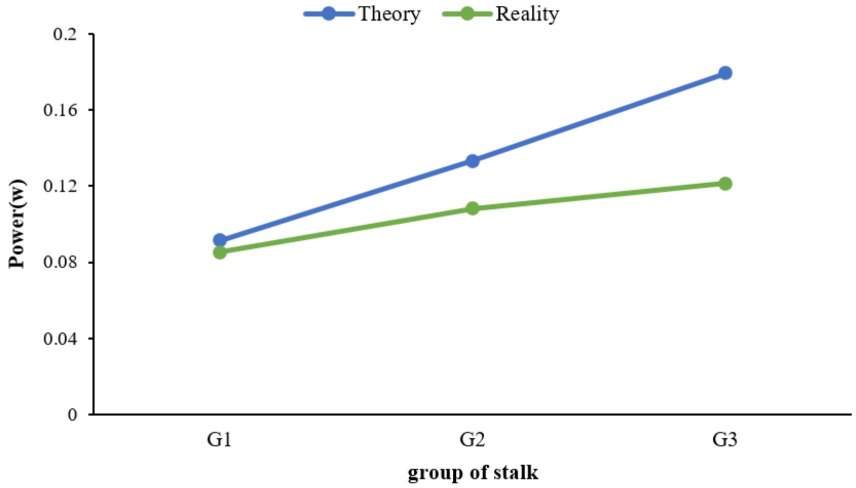


Figure 12 Shear power vs stem number category

4 Conclusions

The effect of speed on force, energy, and cutting power required in fresh alfalfa stalks was investigated. Also, the effect of cumulative cutting of alfalfa stems in certain cutting patterns was studied and the values obtained by the device in cumulative cutting were compared with theoretical data. The results show that force, energy, and cutting power increase with increasing diameter. Also, with increasing force speed, shear stress and energy decrease while shear power increases. In examining shear force, the results show that the force component in groups G1, G2, and G3 at V4 speed has decreased by 52%, 51% and 31%, respectively. In the study of shear energy, it was observed that with increasing diameter, shear energy increases in all treatments. By comparing the shear energy at V4 speed with V1 speed in categories D1, D2, and D3, the results show that the shear energy is reduced by 20%, 25%, and 13%, respectively. In examining the required shearing power of alfalfa stem, the results showed that the shearing power increased with the increase in diameter. By comparing the cutting power at V4 speed with V1 speed in categories D1, D2, and D3, the results show that the cutting power at V4 speed is 2.24 times, 3 times, and 2.64 times the cutting power at V1, respectively.

In the shear analysis of multiple groups of stems, it was observed that the force in G1 groups is equal in reality and theory, while in G2 and G3 groups, the practical shear force is 26% lower than the theoretical value. The practical shear energy in G1, G2 categories is 12%, 7% higher than the theoretical value, respectively, while in G3, the practical shear energy is 4% lower than the theoretical shear energy. The shear strength of the groups in G1, G2 and G3, the practical shear strength is 6%, 19% and 32% less than the theoretical value, respectively.

Acknowledgments

The authors would like to thank the University of Tehran and Shahid Chamran University of Ahvaz for providing the laboratory facilities and financial support for this project. They also appreciate Farzad Mohammadi and Ali Abdisaray for their unstinting assistance.

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Nomenclature

E_s	Shearing energy (J)
L_s	Cut length(mm)
Vi	Cut speed (mm min^{-1})
τ_s	shear strength (MPa)
A	cross-section area of wall (mm^2)
T	Shear time (Second)
P_s	Shear power (W)
D_i	Average diameter (mm)
G_i	Group of multiple stems
F_s	Shear force (N)