

Article

Study on the Shear and Bending Mechanical Properties of Millet Stem

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Abstract: To determine the patterns and influencing factors of the mechanical properties of millet stems from different varieties during the maturity period, this study employed a complete block experiment method and conducted shearing and bending tests on millet stems using the INSTRON5544 electronic universal material testing machine. The research investigated the variation in the shear strength, specific shear energy, bending strength, elastic modulus, and bending stiffness at different internode positions of the stems of Changza 466, Zhangza 16, and Jingu 21 during their maturity period. The results indicated that the variety had a significant impact on the mechanical properties of millet stems: from largest to smallest, the order of shear and bending forces was Jingu 21, Zhangza 16, and Changza 466. The shear strength and bending strength of Jingu 21 were the greatest among the three stem samples. The internode position significantly affected the shear mechanical properties of the millet stems, showing a general trend of decreasing shear strength with ascending internode position. The effect of the internode position on the bending stiffness was highly significant, whereas its impact on the bending strength and elastic modulus was not significant. The shear strength of the millet stems ranged from 3.866 ± 1.086 to 6.953 ± 2.208 MPa, significantly lower than the bending strength, which ranged from 18.934 ± 4.374 to 34.286 ± 6.875 MPa. The lowest shear strength and specific shearing energy, recorded at the fifth internode, were 4.028 ± 1.918 MPa and 15.097 ± 12.633 MJ/mm², respectively. Jingu 21 and Changza 466 exhibit better lodging resistance than Zhangza 16. It is recommended to use a cutting-type platform for harvesting millet stems, with the cutting height set at the fifth internode position. This study provides a theoretical basis for the design of millet harvesting machinery and the selection of harvest parameters.

Keywords: millet stem; shear strength; specific shear energy; bending strength; bending stiffness; elastic modulus



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1. Introduction

Millet, which belongs to Poaceae, is one of the characteristic minor cereal crops of Shanxi Province, known for its drought and barren environment tolerance, stable yield, and high nutritional content. As a principal crop in China's dryland agriculture, millet has always held a significant position [1]. Additionally, being rich in proteins, minerals, and vitamins, millet plays a key role in improving dietary patterns and adding value to agricultural products, thus contributing positively to society. However, the relatively thin stature and softer stems of millet plants make them incompatible or less efficient with the improved large combine harvesters designed for rice and wheat, severely hindering the development of the millet industry [2,3]. The weight of millet heads causes bending deformations in the stems, with heavier heads leading to greater deformation. This bending

and twisting of the stems during harvesting results in grain loss, making the mechanical study of millet stems valuable for practical application.

The mechanical parameters of the stems provide a reference for the mechanized production of crops [4]; plant stems have a complex structure and are capable of resisting various types of loads [5], and test methods are used to obtain the parameters include compression [6], shearing [7], bending [8], and tensile [9] tests. The mechanical strength of the stem is affected by factors such as stem size, moisture content, internode position, and loading rate, each to varying extents [10–15]. The morphology and mechanical characteristics of the stems vary among different crops [16]. There are already some achievements regarding the mechanical properties of millet; Li et al. [17] and Wang [18] conducted tensile tests on the stem, panicle, sheath, and leaves of millet, comparing the binding strength between different parts. Zhang [19] performed tensile tests on millet stems and fibers, finding that the primary load-bearing parts of both Jingu 21 and Qinzhou Huang were the phloem. Tian et al. [20] measured six stem and root traits related to lodging in the field and found that lodging was associated with stem quality but not with stem base height or internode length. Millet is usually harvested by cutting off the stems [21], but the strength of stems at different internode positions varies [22], as does the energy consumed by shearing [23]. Stem lodging is related to bending strength [24], so the study of the bending mechanical properties of stems is important for improving lodging resistance.

During the mature stage, millet stems carry heavier grains [25], and the mechanical properties of the stems determine whether the crop can resist the physical pressures caused by natural conditions (such as strong winds and heavy rains) to avoid lodging losses. Furthermore, the mechanical properties of millet stems during the mature stage are crucial for the design of suitable harvesting machinery that can reduce mechanical damage and improve harvesting efficiency. Therefore, in order to improve the efficiency of grain harvesting operations during the maturity period, to improve the suitability of operating machinery and crops, and to accurately assess and compare the structural stability and mechanical strength of different cereal varieties, this study focuses on the stems of Changza 466, Zhangza 16, and Jingu 21, which are widely cultivated in Fanshi County, Shanxi Province. By conducting shearing and bending tests on millet stems, this study analyzes the shearing and bending mechanical properties of different varieties of millet stems at different internode positions. It aims to reveal the patterns of how the millet variety and the internode position affect stem strength, providing a basis for optimizing millet harvesting equipment and selecting operational parameters.

2. Materials and Methods

2.1. Experimental Materials

Three varieties of millet (Changza 466, Zhangza 16, and Jingu 21), which are widely grown in Fanshi County, Shanxi Province, were selected for the shearing and bending experiments. The stems were selected on 8 October 2023, during their maturity phase. For each variety, ten well-grown, disease-free, complete millet stems were selected. The average height of Changza 466 was measured at 130.6 ± 10.7 cm with 15 nodes, Zhangza 16 at 125.0 ± 9.5 cm with 15 nodes, and Jingu 21 at 152.0 ± 14.0 cm with 16 nodes. For each variety, eight plants were selected, and internode sections were cut from the root base, with the leaves being circumferentially stripped, wrapped in plastic bags, and labeled with the variety number for indoor testing. Of these, six plants were used for mechanical testing and two for measuring the stem moisture content.

2.2. Experimental Instruments and Equipment

An INSTRON5544 electronic universal material testing machine (with a maximum load of 2 kN and ± 0.01 N accuracy) was used to conduct shearing and bending tests on the stem specimens. A 3KFG-01 DHG series heating and drying oven (with a temperature adjustment range of 50–200 °C); an electronic analytical balance, model FA2104S, from Shanghai Precision Instruments and Equipment Limited Company (with a weighing ad-

justment range of 0–60 g and ± 0.1 mg accuracy); and an electronic digital display caliper (with a length adjustment range of 0–150 mm and ± 0.01 mm accuracy) were also part of the equipment used.

2.3. Experimental Methods and Data Processing

Considering that the mechanical harvesting of millet typically involves cutting at a height of 15–40 cm from the ground, the stems were segmented from the base upward, marking five nodes in sequence. The geometric dimensions of each segment were measured and recorded using a digital vernier caliper. Before the experiment, the moisture content of the millet stems for Changza 466, Zhangza 16, and Jingu 21 were tested by the drying method [26], with moisture contents of 74.0%, 76.0%, and 71.7%, respectively. The water content of the stems is related to the growth period, and the test stems were selected at the same period with small differences in water content, so the effect of the water content on the stem strength was ignored in this experiment. The internodal sections were used as samples; the shearing test was carried out by placing the stem specimen in a through-hole of 15 mm diameter in the upper cylinder of the fixture, and then, the upper cylinder was pressed into the lower circular pass to start the shearing test. During the bending test, the stem samples were placed horizontally on two supporting fixtures with a span of 40 mm, ensuring that the axial direction of the specimen was perpendicular to the loading direction, and the test commenced at the instant of contact between the indenter and the stem. At this time, the stems were fixed by the supporting fixtures and the cutter (indenter), and the stems would not roll or flip. The shear and bending tests were conducted using material mechanics methods. The experimental factors included varieties (Changza 466, Zhangza 16, and Jingu 21) and loading positions (1st, 2nd, 3rd, 4th, and 5th nodes), with the loading speed set at 10 mm/min, and each set of mechanical tests was repeated three times.

The cross-section of a millet stem is close to cyclic annular. The formulas for calculating their geometric characteristics and mechanical indices are shown in Equations (1)–(8).

$$\text{Area, } A = \frac{\pi}{4} [d^2 - (d - t)^2] \quad (1)$$

$$\text{Inertial Moment, } I = \frac{\pi}{64} [d^4 - (d - t)^4] \quad (2)$$

$$\text{Shear strength, } \tau = \frac{F_{j\max}}{A} \quad (3)$$

$$\text{Specific shear energy, } E_{sc} = \frac{E_s}{A} = \frac{\int_0^s F_j ds}{A} \quad (4)$$

$$\text{Maximum bending moment in bending, } M = \frac{F_{w\max} l}{4} \quad (5)$$

$$\text{Bending section modulus, } W = \frac{\pi d^3}{32} \left(1 - \frac{(d - t)^4}{d^4} \right) \quad (6)$$

$$\text{Bending strength, } \sigma = \frac{M}{W} \quad (7)$$

$$\text{Elastic modulus, } E = \frac{F_{w\max} l^3}{48 I \delta} \quad (8)$$

where d is the average outer diameter at the point of force application on the specimen, mm; t is the double-sided wall thickness of the stem, mm, measured by vernier calipers and averaged over a number of measurements—the value of t was found to be 25% of the average outer diameter of the stems; A is the cross-sectional area, mm^2 ; I is the moment of inertia of the stem's elliptical cross-section, mm^4 ; $F_{j\max}$ is the maximum shearing force, N; F_j is the shearing force, N; τ is the shear strength, MPa; τ is the shear strength, MPa; E_{sc} is the specific shear energy, MJ/mm^2 ; $F_{w\max}$ is the maximum bending force, N; l is the

support span, 40 mm; and δ is the bending deflection at the point of force application on the specimen, mm.

The shearing test is illustrated in Figure 1a, and the bending test is illustrated in Figure 1b. Once the experiment started, the equipment automatically collected data and plotted the load–displacement curves.

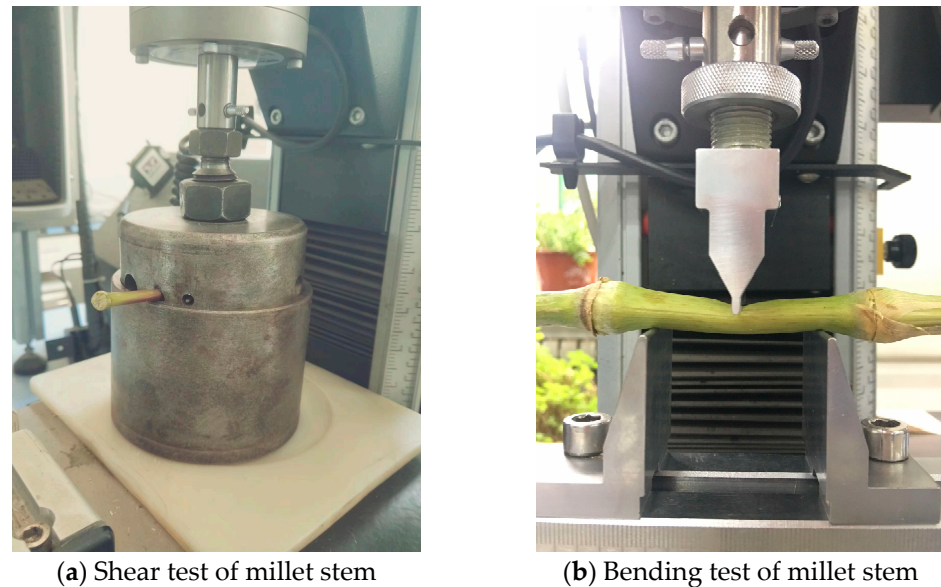


Figure 1. Tests on mechanical properties of millet stems.

Data processing was conducted using Excel 2016. The figures were produced using Origin 9.0, and the analysis of variance (ANOVA) was preformed using the SPSS 18.0.

3. Experimental Results and Analysis

3.1. Mechanical Characteristics of Millet Stem Shear

3.1.1. Influence of Internode Position on Stem Shearing Force

The average outer diameter and internode length of different varieties of millet stems are shown in Table 1. It can be seen that the average outer diameters of the different millet varieties varied between 7.78 mm and 9.90 mm, showing some differences. Among them, some internodes of Zhangza 16 (especially the second internode) had a larger average outer diameter, reaching 9.90 mm, while some internodes of Jingu 21 (especially the fifth internode) had the smallest average outer diameter, at 7.78 mm. The differences in internode length were more significant, ranging from 52.53 mm to 97.75 mm. The fourth and third internodes of Jingu 21 had the longest internode lengths of 97.75 mm and 95.84 mm, respectively, but the second internode of Zhangza 16 had the shortest internode length of 52.53 mm.

Table 1. The average outer diameter and internode length of different varieties of millet stems.

Variety	Internode Position	Average Outer Diameter (mm)	Internode Length (mm)
Jingu 21	The 1st internode	8.16 ± 0.58	67.56 ± 11.89
	The 2nd internode	8.38 ± 0.34	73.71 ± 9.75
	The 3rd internode	8.06 ± 0.30	95.84 ± 17.40
	The 4th internode	8.03 ± 0.35	97.75 ± 10.97
	The 5th internode	7.78 ± 0.64	88.61 ± 28.85

Table 1. Cont.

Variety	Internode Position	Average Outer Diameter (mm)	Internode Length (mm)
Zhangza 16	The 1st internode	9.00 ± 0.20	55.52 ± 4.61
	The 2nd internode	9.90 ± 0.76	52.53 ± 2.70
	The 3rd internode	9.50 ± 0.83	62.52 ± 7.24
	The 4th internode	8.45 ± 0.09	66.66 ± 1.33
	The 5th internode	8.26 ± 0.61	73.43 ± 8.11
Changza 466	The 1st internode	9.57 ± 0.17	63.09 ± 8.43
	The 2nd internode	9.61 ± 0.18	63.31 ± 10.06
	The 3rd internode	8.93 ± 0.14	69.59 ± 15.74
	The 4th internode	8.77 ± 0.23	74.41 ± 22.56
	The 5th internode	8.09 ± 0.09	83.56 ± 16.38

The trend of the shearing force–deformation curve for the three kinds of millet stems was similar. The stem shearing force–deformation curve made using Changza 466 as an example is shown in Figure 2, and the specific shear energy could be calculated by the area of the curve and the horizontal axis. It can be observed that the shear curves of the millet stems all exhibited nonlinear characteristics, with the maximum shearing force being resisted by the first internode of the stem. In the initial phase of shearing, the shearing force at different internode positions of the stem increased with the shear displacement, but the rate of increase gradually decreased. At this stage, the cutter acted on the phloem of the stem. When the displacement reached 2.0–2.5 cm, the cutter acted on the xylem of the stem, the internal structure of the xylem including conduit, wood parenchyma cells may collapse, leading to a decrease in shearing force with increasing shear displacement. At this stage, cracking occurred at the location of the shear force. Since the shearing force squeezed the hollow stem and the stem of high moisture content was soft and flexible, the upper and lower xylem were infinitely close to each other while the pith was compressed, leading to an increase in the shearing force as the shear displacement increased. After reaching the maximum shearing force, the cracks in the stem completely penetrated, and the shearing ended.

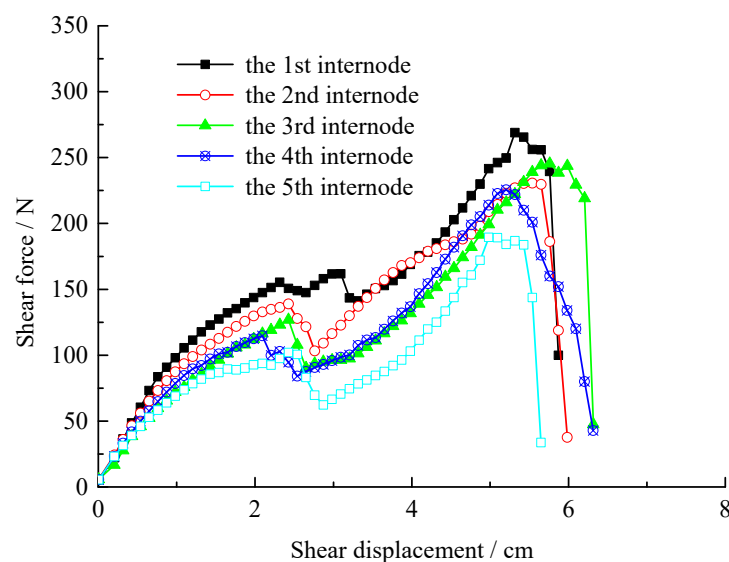


Figure 2. The shearing force–displacement curves at different internode positions.

3.1.2. Influence of Variety on Stem Shearing Force

Figure 3 shows the shearing force–deformation curves for the first internode of the three millet stems. The shear curves of the first internode of the millet stems showed nonlinear characteristics. The shearing force increased as the deformation increased, but

the rate of increase gradually decreased. Among the varieties, Jingu 21 required the smallest shear displacement to reach the maximum shearing force. The order of shear failure force from largest to smallest was Jingu 21, Zhangza 16, and Changza 466.

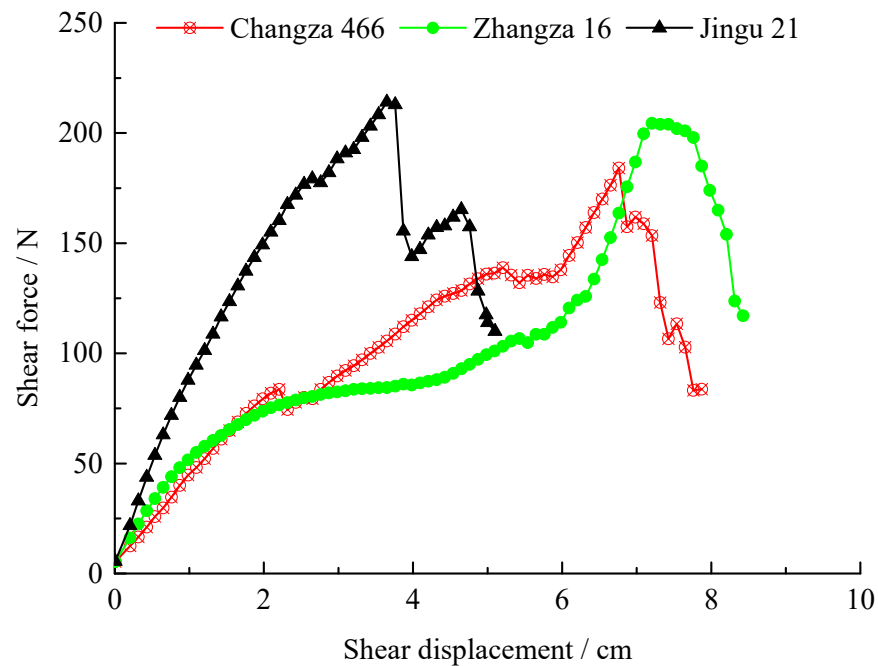


Figure 3. The shearing force–displacement curves of different varieties.

3.1.3. Influence of Varieties and Internode Positions on Shear Parameters

The maximum shearing force and deformation of different varieties of millet stems at different internode positions were determined by shearing tests. The shear strength and specific shear energy were calculated using the formulas mentioned earlier, and the results are shown in Table 2. From the F values in Table 3, it can be observed that the order of the impact magnitude on stem shear strength was variety > internode position.

Table 2. Shearing test results of different varieties of millet stems.

Variety	Internode Position	Shear Strength (MPa)	Specific Shear Energy (MJ/mm ²)
Jingu 21	The 1st internode	9.472 ± 0.839 aA	31.732 ± 10.825 aB
	The 2nd internode	7.096 ± 0.49 abA	14.489 ± 1.935 bB
	The 3rd internode	5.599 ± 1.197 bA	13.163 ± 3.773 bB
	The 4th internode	6.555 ± 1.852 bA	19.946 ± 7.993 abB
	The 5th internode	3.544 ± 0.459 cB	8.916 ± 3.299 bB
Zhangza 16	The 1st internode	7.888 ± 1.004 aA	53.441 ± 13.942 aA
	The 2nd internode	6.648 ± 1.216 aA	46.001 ± 12.561 aA
	The 3rd internode	6.331 ± 1.200 aA	38.696 ± 13.664 aA
	The 4th internode	7.036 ± 1.695 aA	40.953 ± 13.284 aA
	The 5th internode	6.084 ± 1.972 aA	30.202 ± 10.301 aA
Changza 466	The 1st internode	4.703 ± 0.951 aB	11.247 ± 1.918 bC
	The 2nd internode	4.683 ± 0.392 aB	16.856 ± 3.735 aB
	The 3rd internode	4.417 ± 0.564 aA	13.708 ± 1.657 abB
	The 4th internode	3.077 ± 0.499 bB	7.042 ± 0.889 cB
	The 5th internode	2.449 ± 0.422 bB	6.172 ± 1.533 cB

Note: Different small letters a, b, c indicate significant differences in shearing characteristics at different internode positions in the same variety at a 0.05 level. Different capital letters A, B, C indicate significant differences in shearing characteristics of different varieties at the same internode position at a 0.05 level.

Table 3. Variance analysis of stem shear test results.

Source of Variance	Freedom	Shear Strength			Specific Shear Energy		
		Mean Square Error	F Value	p Value	Mean Square Error	F Value	p Value
Variety	2	35.518	31.214	<0.001	3955.412	56.244	<0.001
Internode Position	4	13.093	10.611	<0.001	346.283	4.924	0.004
Variety * Internode Position	8	2.838	2.3	0.047	85.103	1.21	0.327
Error	30	1.234			70.325		
$R^2 = 0.804$					$R^2 = 0.825$		

From Tables 3 and 4, it can be seen that the variety had a highly significant impact on both the stem shear strength and the specific shear energy ($p < 0.001$). Changza 466 had lower shear strength, measured at 3.866 MPa, while Jingu 21 and Zhangza 16 exhibited a higher shear strength and measured at 6.953 MPa and 6.797 MPa, respectively. There was a significant difference in specific shear energy among the different varieties, with Zhangza 16 having the highest specific shear energy, followed by Jingu 21 and Changza 466, with 41.860 MJ/mm², 17.650 MJ/mm², and 11.010 MJ/mm², respectively.

Table 4. Influence of variety and internode position on stem shear performance.

Independent Variable		Shear Characteristics	
		Shear Strength (MPa)	Specific Shear Energy (MJ/mm ²)
Variety	Jingu 21	6.953 ± 2.208 a	17.650 ± 9.819 b
	Zhangza 16	6.797 ± 1.398 a	41.860 ± 13.461 a
	Changza 466	3.866 ± 1.086 b	11.010 ± 4.544 b
Internode Position	The 1st internode	7.354 ± 2.253 a	32.140 ± 20.315 a
	The 2nd internode	6.142 ± 1.305 ab	25.782 ± 16.579 ab
	The 3rd internode	5.449 ± 1.224 b	21.856 ± 14.509 ab
	The 4th internode	5.556 ± 2.267 b	22.647 ± 16.734 ab
	The 5th internode	4.028 ± 1.918 c	15.097 ± 12.633 b

Note: Different lower-case letters after the data in the same column indicate significant differences under the same independent variable ($p < 0.05$).

Tables 3 and 4 show that the internode position had a highly significant effect on the shear strength ($p < 0.001$) and the specific shear energy ($p = 0.004$). The shear strength of the stems varied with different internode positions, with the highest shear strength at the first internode, valued at 7.354 MPa, and the lowest at the fifth internode, valued at 4.028 MPa. The second, third, and fourth internodes were of intermediate shear strength with minor differences between them. The reason for this was that the lower part of the stem was more mature, and its tissues were more developed than the upper part, resulting in greater toughness and higher shear strength at the first internode. The upper part of the stem, being less mature and having a lower cellulose content [27], resulted in the lowest shear strength at the fifth internode. The specific shear energy decreased as the internode position increased. The shear strength and specific shear energy of the fifth internode decreased by 54.7% and 47.0%, respectively, compared to the first internode. When harvesting millet, choosing the appropriate cutting position can reduce power consumption.

3.2. Mechanical Characteristics of Millet Stem Bending

3.2.1. Influence of Internode Positions on Stem Bending Force

Figure 4 shows the bending force–displacement curves for the bending test of Jingu 21 stems. It was observed that the bending curves of millet stems exhibited nonlinearity, and the first internode of the stem could resist the maximum bending force, which required the largest displacement for bending failure. In the initial stage of bending, the bending

force of different internode positions increased approximately linearly with the increase in displacement, and the lower the internode position, the faster the increase in bending force. When the displacement reached 1.8 cm, the bending force of the fifth internode gradually decreased, attributed to the smaller stem size at this position, resulting in a reduced ability to resist bending force. When the displacement reached 2.2 cm, the bending force of the fourth internode also gradually decreased. With the increase in bending displacement, the bending force of each internode reached its maximum and then decreased. Cracks appeared at the bending point of the stem and gradually extended.

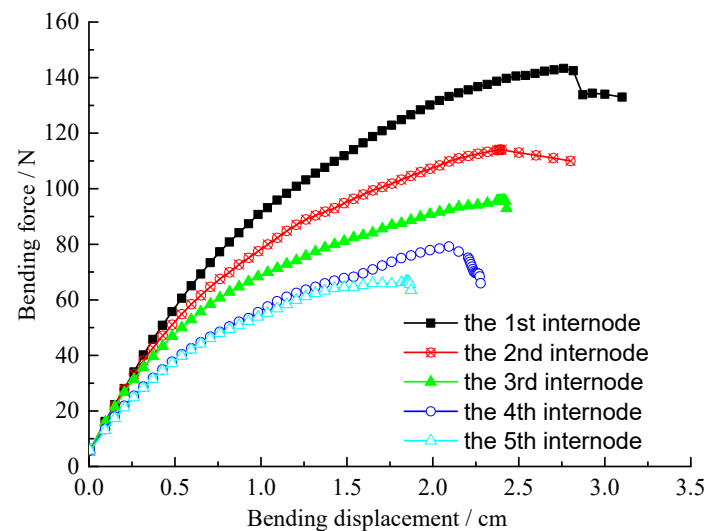


Figure 4. The bending force–displacement curves at different internode positions.

3.2.2. Influence of Variety on Stem Bending Force

Figure 5 illustrates the bending force–deformation curves for the first internode of the three millet stem varieties. It can be observed that the curves obtained from the first internode of the three varieties all exhibited nonlinearity. The bending force increased as the deformation increased, but the rate of increase gradually decreased. When the deformation reached about 2.2 cm, the bending force of Changza 466 started to decrease. When the deformation reached approximately 3 cm, the bending force of Jingu 21 began to decrease, and while Zhangza 16 showed an increasing trend in bending force, it eventually reached a stable state. The order of bending failure force from largest to smallest was Jingu 21, Zhangza 16, and Changza 466. The displacement sequence of bending failure from smallest to largest was Changza 466, Jingu 21, and Zhangza 16.

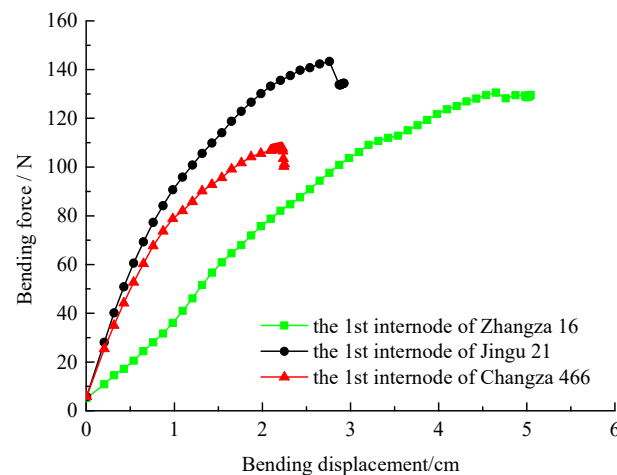


Figure 5. The bending force–displacement curves of different varieties.

3.2.3. Influence of Variety and Internode Position on Bending Parameters

The maximum bending force and deformation of millet stems of different varieties at different internode positions were measured by bending tests. The bending strength, elastic modulus, and bending stiffness (EI) were calculated using the formulas mentioned before, and the bending test results are presented in Table 5. From the F values in Table 6, it can be observed that the order of the impact magnitude on stem bending strength was variety > internode position.

Table 5. Bending test results of millet stems from different varieties.

Variety	Internode Position	Bending Strength (MPa)	Elastic Modulus (MPa)	Bending Stiffness (kN·mm ²)
Jingu 21	The 1st internode	40.374 ± 7.487 aA	631.353 ± 56.662 aA	71.604 ± 19.399 aA
	The 2nd internode	35.592 ± 6.254 aA	601.076 ± 407.298 aB	54.277 ± 15.643 aAB
	The 3rd internode	32.017 ± 7.508 aA	478.474 ± 98.212 aA	45.352 ± 21.542 aA
	The 4th internode	31.720 ± 6.988 aA	580.230 ± 208.847 aB	40.306 ± 8.620 aA
	The 5th internode	31.726 ± 6.704 aA	582.048 ± 16.477 aA	42.600 ± 10.070 aA
Zhangza 16	The 1st internode	23.290 ± 4.337 aB	225.243 ± 65.691 aA	45.277 ± 14.106 aA
	The 2nd internode	20.652 ± 3.881 aB	145.736 ± 32.613 aB	21.711 ± 4.122 bB
	The 3rd internode	17.899 ± 3.584 aA	147.496 ± 45.169 aA	16.636 ± 2.088 bB
	The 4th internode	16.550 ± 2.744 aB	216.116 ± 78.960 aB	16.850 ± 1.832 bA
	The 5th internode	16.277 ± 5.104 aB	216.092 ± 13.858 aA	13.364 ± 3.864 bB
Changza 466	The 1st internode	34.189 ± 1.020 aA	398.007 ± 140.670 aA	90.696 ± 29.894 aA
	The 2nd internode	28.773 ± 5.665 aAB	345.527 ± 97.089 aB	60.681 ± 26.408 abA
	The 3rd internode	28.621 ± 11.303 aA	417.250 ± 274.269 aA	49.406 ± 8.130 bA
	The 4th internode	26.335 ± 10.194 aAB	404.846 ± 10.991 aB	36.807 ± 17.873 bA
	The 5th internode	28.457 ± 5.911 aA	435.369 ± 08.823 aA	30.066 ± 13.183 bAB

Note: Different small letters a, b indicate significant differences in bending indexes at different internode positions in the same variety at a 0.05 level. Different capital letters A, B indicate significant differences in bending indexes of different varieties at the same internode position at a 0.05 level.

Table 6. Variance analysis of stem bending test results.

Source of Variance	Freedom	Bending Strength			Elastic Modulus			Bending Stiffness		
		Mean Square Error	F Value	p Value	Mean Square Error	F Value	p Value	Mean Square Error	F Value	p Value
Variety	2	919.355	22.052	<0.001	555,986.6	10.482	0.002	4352.673	17.889	<0.001
Internode Position	4	89.133	2.138	0.101	8535.414	0.161	0.617	2399.941	9.863	<0.001
Variety * Internode Position	8	3.029	0.073	1	4793.365	0.09	0.811	150.218	0.617	0.756
Error	30		41.691			1,591,301.745			7299.592	
			R ² = 0.640			R ² = 0.427			R ² = 0.728	

Tables 6 and 7 indicate that the variety had a highly significant impact on the stem bending strength, elastic modulus, and bending stiffness ($p < 0.001$). There was considerable variation in the bending strength among varieties, with the highest to lowest being Jingu 21, Changza 466, and Zhangza 16 with values of 34.286 MPa, 29.275 MPa, and 18.937 MPa, respectively. The elastic modulus was the highest for Jingu 21 at 574.636 MPa, followed by Changza 466, and Zhangza 16 had the lowest elastic modulus. Zhangza 16 had the lowest bending stiffness at 22.768 kN·mm², while Jingu 21 and Changza 466 had similar bending stiffness values. From the perspective of bending indicators, Zhangza had the lowest bending parameters, while Jingu 21 had the highest, indicating that Jingu 21 had better lodging resistance.

Table 7. Impact of variety and internode position on stem bending performance.

Independent Variable		Bending Characteristics		
		Bending Strength (MPa)	Elastic Modulus (MPa)	Bending Stiffness (kN·mm ²)
Variety	Jingu 21	34.286 ± 6.875 a	574.636 ± 265.218 a	50.828 ± 17.883 a
	Zhangza 16	18.934 ± 4.374 c	190.136 ± 71.886 c	22.768 ± 13.320 b
	Changza 466	29.275 ± 7.081 b	400.200 ± 208.169 b	53.531 ± 28.208 a
Internode Position	The 1st internode	32.617 ± 8.665 a	418.200 ± 262.641 a	69.193 ± 27.519 a
	The 2nd internode	28.339 ± 7.970 a	364.113 ± 288.383 a	45.556 ± 23.818 b
	The 3rd internode	26.179 ± 9.485 a	347.740 ± 254.5711 a	37.131 ± 19.313 b
	The 4th internode	24.868 ± 9.188 a	400.398 ± 248.015 a	31.321 ± 14.811 b
	The 5th internode	25.487 ± 8.729 a	411.169 ± 253.455 a	28.676 ± 15.293 b

Note: Different lower-case letters after the data in the same column indicate significant differences under the same independent variable ($p < 0.05$).

The poor fitting result of elastic modulus is related to the measurement error of stem deformation. The thickness of the stems affected the amount of deformation measurements, and the test estimated the deformation after bending of the stems under force. However, the range of elastic modulus of the analyzed stems was close to the results of Zhang [23], which indicated that the results of the analysis were reliable.

From Tables 6 and 7, it can be seen that internode position had an extremely significant impact on the bending stiffness ($p < 0.001$), but its influence on the bending strength and elastic modulus was not significant. The bending stiffness of the first internode of millet stems was significantly higher than that of other internodes, measuring 69.193 ± 27.519 kN·mm². The bending stiffness of the fourth and fifth internodes was comparatively lower.

4. Discussion

In general, grain harvesting involves cutting the stems, and the study of the shearing and bending mechanical characteristics of millet stems is of great significance for reducing energy consumption and improving efficiency. The shear curves for millet obtained in this study were found to closely resemble those for wheat [28], barley straw [29], and glabra [30], highlighting a similar mechanical behavior among these plant types. In contrast, the shearing curves differed significantly from sainfoin stems [14], suggesting that the variation may be attributed to differences in the internal structure of the stems. This distinction underscored the importance of understanding the unique anatomical characteristics that influence the mechanical properties of different plant species. For the three varieties of millet studied, the first internode of the stem exhibited the highest shear strength, while the patterns of shear strength for the second, third, fourth, and fifth internodes were not distinct. This conclusion differed slightly from the findings of Wu et al. [31] in their study of millet straw. The difference was attributed to Wu's selection of overwintered straw, which had a lower moisture content, leading to larger differences in shear strength between internodes. The shear strength of Jingu 21 and Changza 466 was lowest at the fifth internode, while in Zhangza 16, the shear strength was lowest at the second and third internodes, increasing by around 8% at the fifth internode. The specific shear energy for all three varieties was lowest at the fifth internode (Figure 6). Therefore, when harvesting the three mature millet varieties selected for this study, it is advisable to choose the cutting position at the fifth internode. This strategic choice optimizes the shearing process, taking advantage of the lowest shear strength and specific shear energy at this point. By targeting the fifth internode, efficiency is maximized, energy consumption is minimized, and the overall harvesting operation is significantly improved.

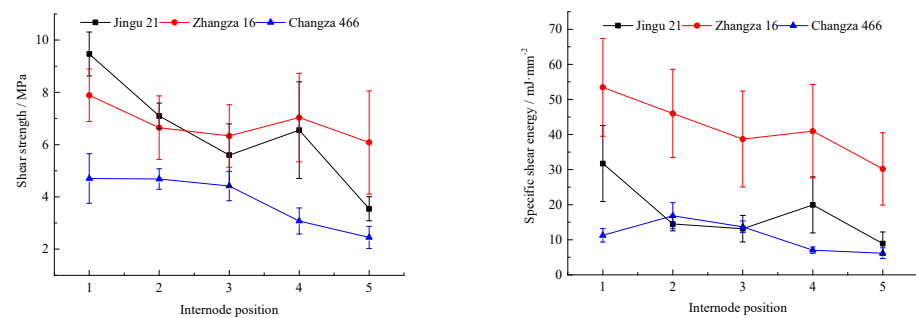


Figure 6. Relationship between internode position and shear strength and specific shear energy.

The elastic modulus can be used as an evaluation indicator for stem lodging resistance [32]. The larger the elastic modulus, the stronger the lodging resistance. Therefore, Jingu 21 and Changza 466 exhibited better lodging resistance than Zhangza 16. Some studies suggested that the greater the unit length dry weight or fresh weight between the first and second internodes at the base, the smaller the lodging index, with the parameters between the first and second internodes at the base having the greatest impact on lodging [33,34]. In our study, the results showed that the elastic modulus of the third internode was the smallest for Jingu 21, while Zhangza 16 and Changza 466 had the smallest elastic modulus at the second internode. Therefore, the millet stems of these three varieties tended to undergo lodging near the second and third internodes. Additionally, comparing the bending strength with the shear strength, it was found that the bending strength of millet stems was significantly greater than the shear strength. This was consistent with the conclusion drawn by Shi et al. [35] from mechanical tests on sesame stems. Therefore, when harvesting millet stems, a cutting-type harvester should be selected, and the cutting height should be set at the fifth internode.

The average outer diameter of the specimens was correlated with the shear index and the bending index, and the effect of the small stem wall thickness was not considered, so the correlation coefficients for each index are shown in Table 8.

Table 8. Correlation between the average outer diameter and the shear and bending indices.

	Average Outer Diameter (mm)	Shear Strength (MPa)	Specific Shear Energy (MJ/mm ²)	Bending Strength (MPa)	Elastic Modulus (MPa)	Bending Stiffness (kN·mm ²)
Average outer diameter	1	0.075	0.238	−0.129	−0.517 **	0.294 **
Shear strength		1	0.738 **	−0.019	−0.007	0.069
Specific shear energy			1	−0.460 **	−0.337 *	−0.250
Bending strength				1	0.750 **	0.663 **
Elastic modulus					1	0.525 **
Bending stiffness						1

* Significantly correlated at the 0.05 level (bilateral). ** Significantly correlated at the 0.01 level (bilateral). Vertical physical quantities have the same units as their horizontal counterparts.

The average outer diameter was weak-positively correlated with the shear strength, specific shear energy, and bending stiffness, and it was weak-negatively correlated with the bending strength and negatively correlated with the elastic modulus. The shear strength and the specific shear energy showed a significant positive correlation. The specific shear energy and the bending strength showed a significant negative correlation. The bending strength had a strong positive correlation with the elastic modulus and the bending stiffness.

5. Conclusions

The mechanical properties of millet stems are crucial parameters for the mechanized harvesting of millet. Through experimental means, the shear and bending characteristics

of millet stems at maturity were studied for three different varieties. The analysis of their mechanical properties led to the following three conclusions:

Both the variety and the internode position significantly influenced the stem's shear strength and specific shear energy. There were significant differences in the shear mechanical properties of stems among the different varieties. As the internode position increased, the overall trend was a decrease in both the stem shear strength and specific shear energy.

The impact of the variety on the stem bending stiffness, elastic modulus, and bending stiffness was extremely significant, and the influence of the internode position on the bending stiffness was highly significant, while its effect on bending strength and elastic modulus was not significant.

The influence of the variety on the mechanical characteristics of the stem was greater than that of the internode position. The shear strength of the millet stems ranged from 3.866 ± 1.086 to 6.953 ± 2.208 MPa, which was significantly lower than the bending strength, ranging from 18.934 ± 4.374 to 34.286 ± 6.875 MPa. The shear strength and specific shear energy at the fifth internode of the millet stem were the lowest, at 4.028 ± 1.918 MPa and 15.097 ± 12.633 MJ/mm², respectively. When harvesting millet, it is recommended to set the height of the cutting table at the fifth node of the stem.

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