Research on Bending Mechanical Properties and Evaluation of Lodging Resistance of Millet Stem

Wu Cuiqing, Guo Yuming, Zhang Jing, Wu Xinhui, Wangsheng

***Abstract*— Crop lodging seriously affects crop production. The significant factors that affect crop lodging are stem shape, anatomical structure, and stalk physical properties. From a macro-mechanics point of view, the paper focuses on investigation of lodging resistance of millet stems and their correlated geometric parameters, such as stem length, section parameters (the long axis, short axis and area) and wall thickness; and biomechanical property indexes, such as cross-section, elastic modulus, flexural rigidity, and bending strength. In addition, the research also aims to develop a biomechanical evaluation method for (1) evaluation of lodging resistance of typical millet crops, such as DunGu, ChangZa, JinGu and ZhangZa, and (2) analysis of the correlation between the biomechanical property indexes mentioned above and stem lodging resistance of several high-quality millet crops. This research is expected to provide a new method to predict lodging resistance of millet stems based on their biomechanical properties for genetic selection of high quality millet crops.**

***Index Terms*— millet stem, biomechanical property, geometric parameters, lodging resistance, Principal factor analysis.**

I. INTRODUCTION

Due to the nature of large and heavy ear and thin stem, millet crop is easy to get flattened, which has a great impact on the millet production. The principal factors affect millet crop lodging are the physical characters of the millet crop stem, such as height, stem thickness, length of internodes and wall thickness of stem at its base. In recent years, chemical composition and structure of millet crop stem along with its biomechanical properties have caused extensive research interests. These properties play an important role in lodging resistance of stalk crops. In addition, they also provide a theoretical support to understand anti-lodging mechanisms and cultivation and breeding of stalk crops. Certain progresses had been achieved in understanding properties of crop stem and its biomechanics and lodging resistance.

In 1976, L.L. Bashford, et al. [1] studied how mechanical properties of sorghum stalks affected the sorghum lodging. Scientists gradually realized that some biomechanical property indexes could be used to express the characteristics of lodging resistance of stalk crops. Liu et al. [2] applied the principles and methods of agrobiomechanics and preliminarily studied the relationship between the organization structure and mechanical property of wheat stem and its lodging. Crook et al. [3] studied the properties of stem lodging and root lodging of four kinds of winter wheat. Kinuma, et al. [4] defined the value of root lodging resistance. Biomechanics laboratory at Chongqing University studied the mesoscopic structure of rice stem and its resistance to lodging, analyzed the relationship between lodging resistance of several varieties of rice and their biomechanical properties, such as fracture resistance, diameter, and stem wall. Yuan Zhihua, et al. [5] conducted a mechanical analysis of lodging resistance of crop stems and indicated several biomechanical indexes related to lodging resistance of stems. Coutand, et al. [6] studied effects of load on tomato stem. Farquhar et al. [7] and DoaréO et al. [8] developed some parameters about the influence of load to deformation and indicated there was a geometrically nonlinear relationship between the intensity of gravity and the frequency of the wind of high-quality wheat stalks. Guo et al. [9-12] systematically conducted research on the mechanical properties and lodging resistance of wheat stem with many research findings including upper limits of compressive and stretching strength between internodes, the elastic modulus, Poisson's ratio, upper limit of bending strength under different moisture contents, biomechanical property indexes, and evaluation methods for stem lodging resistance. Although achievements have been made about biomechanical evaluation of lodging resistance of stem crops. For different millet varieties in different growth periods, experimental studies in consideration of different factors still need to be conducted.

The study intends to find an evaluation method and approaches for choosing high-quality millet seeds according to their applied biomechanics. The specific objectives of this paper are to (1) analyze biomechanical property indexes; (2) develop an evaluation method for lodging resistance of millet, such as ChangZa, JinGu and ZhangZa; and (2) conduct correlation analysis between biomechanical property indexes, lodging resistance, and millet bending performance, such as cross-section, elastic modulus, bending rigidity, and bending strength of several high-quality millet stalks. This research results are expected to provide a new method to predict lodging resistance of millet stems based on their biomechanical properties for genetic selection of high quality millet crops.

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II. Materials and Methods

1.1 Sample Collection

The bending tests used samples of three kinds of millets, which are breeding seeds produced from the experimental plot of Shanxi Agricultural University. The sampling time was during the period of millet maturity. Six samples from each kind of millet were selected. The samples were preprocessed to remove root, leaf, and leaf sheath and then measured for height, spike length, and spike weight. Further more, the samples were cut into subsamples from the sample base node to the internodes in a sequential manner. The outer diameter and wall thickness of the subsamples were then measured using vernier caliper taking the average of three measurements.

1.2 Test Equipment and Method，

An electrical universal material testing machine (SANS-CMT6104, Shenzhen SANS Testing Machine Co., Ltd, China) was used to test the properties of the subsamples static bending. The equipment was controlled by a computer, 200 N sensor with 5% precision and a loading rate of 10 mm/min (figure 1), an electronic balance with an resolution of 0.01 g, and a vernier caliper, etc.

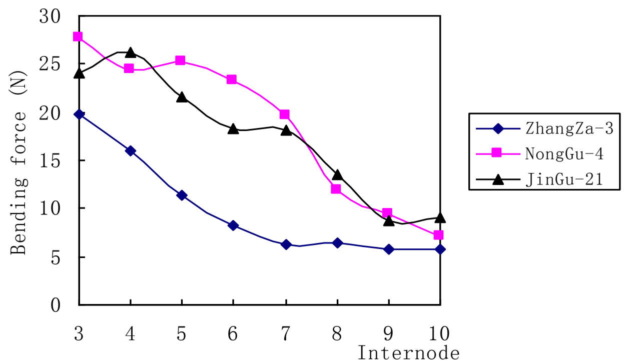
The bending property values of the material in each internode of the millet have been tested. On the stage of bending loading after preloading stress, the equipment automatically recorded the experimental values and dynamically drew the load-displacement curves. The maximum bending load for an effective subsamples was obtained from the condition that some of the material components starts to fail. The bending strength of millet stalk is $\sigma_{弯} = \frac{M}{W} = \frac{Fdl}{8I}$, and the modulus of elasticity is $E = \frac{Fl^3}{48Iw}$. Where, M is the bending moment, N·m; W is the section modulus in bending, mm3; F is The maximum bending load of millet stalk, N; d is the external diameter of millet stalk, mm; l is the standard moment, mm; I is the moment of inertia of cross-section,mm4; w is deflection in bedding, mm.

Fig 1 A test equipment for measurement of bending properties of millet stems.

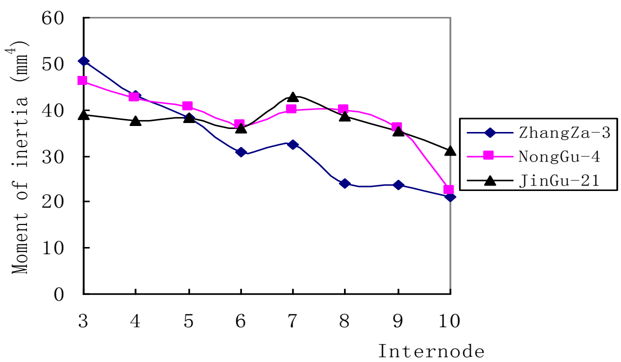
III. Results and Discussions

As shown in figure 2, the indexes of millet's bending properties change with the millet stem height. There are great differences in the mechanical properties of different varieties of millet. The bending forces of different varieties decrease steadily as the stem height increases, but with different decline rates. Among the three varieties of millet crop, ZhangZa-3 has the lowest bending force. The moment of inertia of cross-section in the hollow circular section of millet stalk is $I_z = \pi(D^2 - d^2)/64$, the decline rates of moment of inertia of cross-section of different varieties are almost the same. Among the three varieties of millet crop, Jingu No.21 is relatively small. The bending strengths has little chance as the stem height increases, except for several kinds, such as Jingu No. 21, whose bending strength lowers, as the height goes up. There are significant differences in the elastic modulus of millet stalks with the changing height. The elastic modulus of ZhangZa-3 changes very little, but elastic modulus of Nonggu No.4 increase as the stem height increases. The elastic modulus changes slightly when the stem height is between 5 and 8 internode. Meanwhile, as the height increase, elastic modulus of Jingu-21 increases between 5 and 8 internodes, and then decreases as the stem height increases. The changes of ZhangZa -3 and JinGu-21 in bending rigidity and elastic modulus are conformed, but as the height increases, bending rigidity of NongGu-4 increases when the stem height is 3-5 internodes. There is no obvious change when the stem height is 5 to 8 internodes, but a sharp increase is observed when the stem height is 8 to 9 internodes.

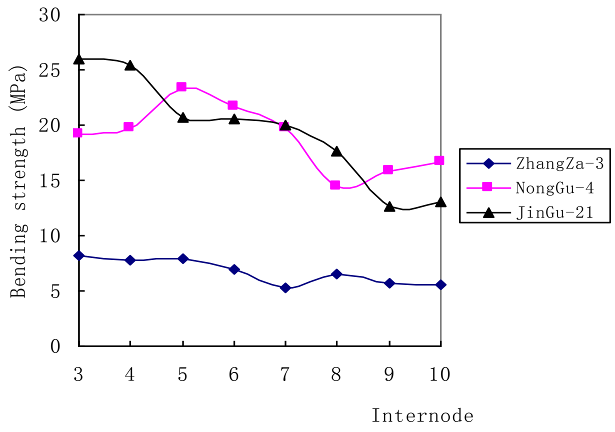
According to the test results of the three varieties of millet stalk, the bending property indexes of ZhangZa-3 are relatively small and their changes are also smaller as it grows. The changing trends of the other two varieties are almost accordant. The biomechanical properties of fine varieties are consistently fine with the entire stem height range. For example, the biomechanical property indexes of ZhangZa-3 are relative stable as the stem height increases. This result indicates that ZhangZa-3 has no obviously weak internodes.



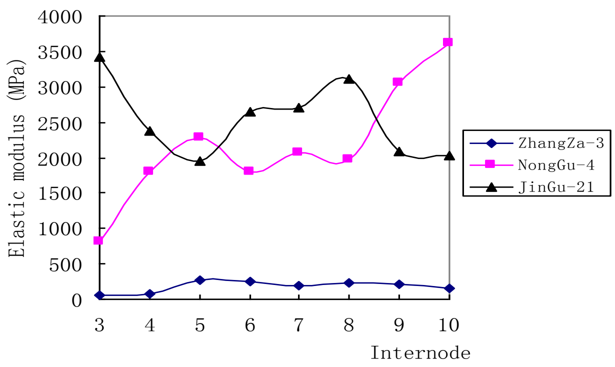
(a) Variations in bending force as millet crop stem height increases



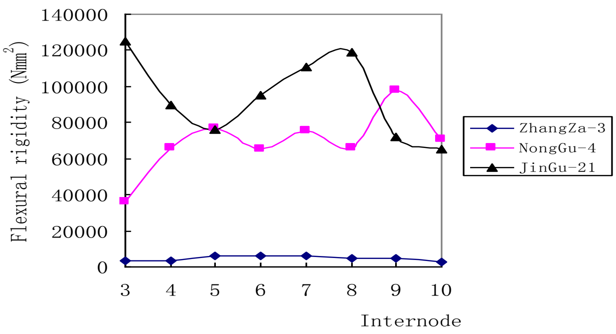
(b) Variations in moment of inertia of cross-section as stem height increases



(c) Bending strength variation curve at different height



(d) Elastic modulus variation curve at different height



(e) Flexural rigidity variation curve at different height

Figure 2 Variations in bending property indexes as stem height increases

IV. Analysis of Influential Factors

Many factors affect lodging resistance of millet crop. There also exists certain correlation between the factors. To explore effects of morphological indexes, such as wall thickness, long axis, short axis, and area, and biomechanical indexes, such as bending strength, deflection, bending force, moment of inertia of cross-section, and elastic modulus, on lodging resistance of millet, a principal component analysis of the test results was conducted using ZhangZa-3 as an example.

We used the princomp process in SAS statistical analysis software (SAS9.2, SAS Institute Inc., USA)and the test data to analyze the principle factors affecting lodging factors. We defined Prin1 as the first principal component of crop morphological index and Prin1′ as the first principal component of crop biomechanical indexes. The results are shown in Tables1-4

Table 1 Results of Principal component analysis with Prin1

Number of Principal component	1	2	3	4
contribution rate	0.9863	0.0102	0.0030	0.0004
accumulating contribution rate	0.9863	0.9965	0.9996	1.0000

Table 2 Eigenvalue of Prin1

original variables	wall thickness	long axis	short axis	area
Eigen value	-0.010335	0.074272	0.056875	0.995561

Table 3 Results of Principal component analysis with Prin1′

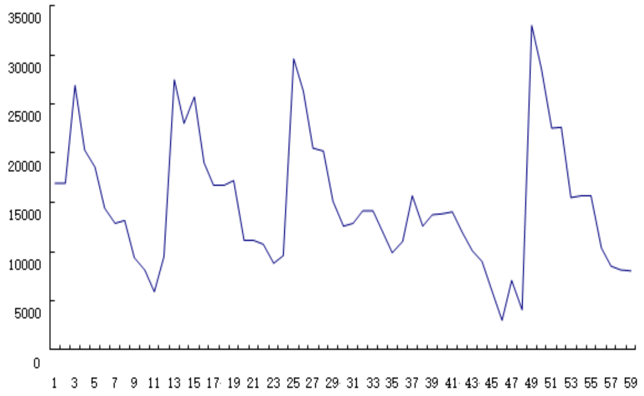
Number of Principal component	1	2	3	4
contribution rate	0.9991	0.0009	0	0
accumulating contribution rate	0.9991	1.000	1.000	1.0000

Table 4 Eigenvalue of Prin1′

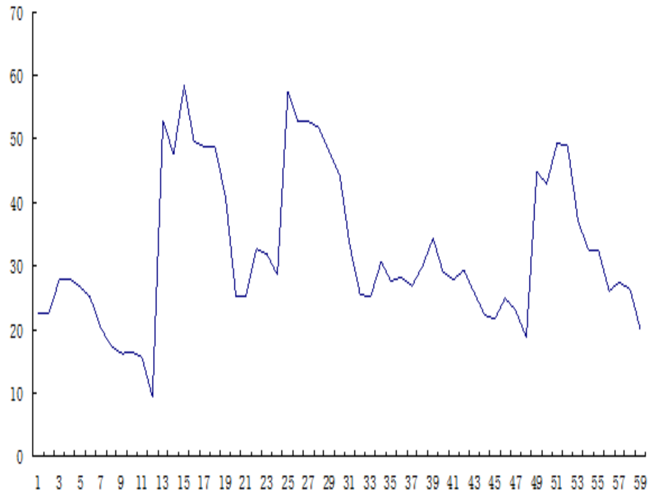
original variables	bending strength	moment of inertia	elastic modulus	bending stiffness
Eigen value	0.000898	0.003709	0.004746	0.999981

As shown in Table 1 and Table 2, in terms of crop morphology index, accumulating contribution rate of the first Principal component reaches up to 0.9863, which is larger than 0.85, a commonly used threshold. This means that Prin1 can explain 98.63% variations in the original four growth characteristics, i.e. Prim1 can account for 98.63% of the total information of crop growth characteristics. Therefore, the first principal component can be used as a standard to analyze the characteristics of crop growth and the other main component as the observation error. In addition, the area takes the largest share up to 0.995561, which indicates that morphological index is mainly determined by the area, whose accumulating contribution rate of the first principal component is 0.9991, the number illustrates that 99.91%

information of the crop's lodging resistance is included in Prin1′ and the proportion of bending stiffness reaches up to 0.999981. Therefore, properties of crops lodging resistance mainly depend on the bending stiffness. The results of Prin1and Prin1′ are illustrated in figure 3.



(a) Prin1 result



(b)Prin1′result

Figure 3. Prin1 and Prin1′ results of ZhangZa-3

Glm process with SAS analyzes variance of Prin1 ', the result is illustrated in Table 5.

Table 5 Varieties and Prin1 ' ANOVA results(1)

Source of variance	Quadratic sum	Degree of freedom	Mean square	F value	Pr>F
model	1784264726	3	594754909	15.64	<.0001
error	7262428156	191	38023184	R^2=0.8023	
sum	9046692882	194			

Table 6 Duncan's multiple range test

Varieties	Mean value	Number of observations	Significance（0.05）
JinGu	14880	59	A
ZahngZa-9	13872	30	A
ZhangZa-3	11301	50	B
ZhangZa5	7394	56	C

The analysis of variance shows that lodging resistances are significantly different between the varieties. The test probability of differences is less than 0.0001. Multiple comparisons are further made and the comparison analysis results are presented in Table 6. The properties of lodging resistance is sorted out by a descending order with a sequence of JinGu, ZhangZa-9, and ZhangZa-5. Duncan's multiple comparisons were conducted with a significance level of 0.05. The mean values don't differ statistically between JinGu and ZhangZa-9, but the mean values of ZhangZa-3 and ZhangZa-5are significantly different from each other and different from ZhangZa-9. Coefficient of determination is 0.8023, which indicates that ANOVA results can explain 80.23% lodging resistance variations and the models are reliable.

V. Conclusions

（1）The bending performance of three millet varieties demonstrated a similar variation trend as the stem height increase. The flexural mechanical properties of fine varieties had no significant changes as the stem increased in the entire height range. For example, the ZhangZa-3's indicators of bending mechanical properties did not change with the stem height and no obvious weak internodal segments existed for ZhangZa-3 millet. .

（2）Flexural properties of the millet morphological indexes mainly include stalk area and shape. The hollow circular shape is directly related to the bending stiffness of the mechanical properties of lodging resistance and greatly improves the bending stiffness and lodging resistance of millet stem. This phenomena reflects the essential characteristics of biological adaptation to the nature.

(3) The analysis of influencing factors indicated that flexural rigidity could be applied to evaluate indexes of mechanical properties of millet lodging resistance, which includes mechanical properties of millet stalks, stem geometry, and stem resistance to bending deformation.

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