SIMULATION AND TEST OF CUTTING MECHANICAL CHARACTERISTICS OF MILLET STALK BASED ON ANSYS/LS-DYNA
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基于 ANSYS/LS-DYNA 的谷子茎秆切割力学特性仿真与试验

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ABSTRACT

In order to find the variations of mechanical properties of millet stalk during dynamic cutting, a three-dimensional model of cutting parts and a double-layer flexible model of millet stalk were established in this study. The mechanical cutting properties of millet stalk at different cutting speeds and blade oblique angles were investigated based on ANSYS/LS-DYNA, while the verification tests were carried out based on the self-made cutting test bench. Simulation results showed that the maximum Von Mises stress was concentrated on the contact point of the stalk and the moving blade. The maximum Von Mises stress of stalk during extrusion, cutting, and after cutting were 60.03 MPa, 60.72 MPa, and 39.87 MPa, respectively, and the cutting energy of stalk epidermal tissue was greater than that of inner tissue. The cutting stress and the unit area cutting energy decreased first and changed steadily as cutting speed was increased when the cutting speed was 0.5-1.5 m/s. When the blade oblique angle was 0°-48°, the cutting stress decreased as the blade oblique angle was increased, while the unit area cutting energy decreased first and then increased. Verification tests showed that the cutting speed and the blade oblique angle had significant effects on the cutting mechanical properties (P < 0.05), which was consistent with the simulation test results. Research results can be used to optimize the cutting parameters of millet stalk.

摘要

为探究谷子茎秆动态切割过程中的力学特性参数变化规律，本文建立了切割部件三维模型与谷子茎秆双层柔性模型，以切割速度与刀片斜角为影响因素，基于 ANSYS/LS-DYNA 对谷子茎秆进行动态切割力学仿真，并采用自制切割试验台进行验证试验。仿真结果表明：茎秆切割过程分为挤压与切割茎秆两个阶段，且最大 Von Mises 应力集中于茎秆与动刀片接触部位，挤压过程、切割过程与切割完成后茎秆最大 Von Mises 应力分别为 60.03 MPa、60.72 Mpa 和 39.87 MPa，且茎秆表皮层较内层切割功耗大。当切割速度为 0.5—1.5 m/s 时，切割应力、单位面积切割功耗随切割速度的增大而减小后呈现平稳变化的趋势；当刀片斜角度 0°—48°时，切割应力随刀片斜角的增大而减小，而单位面积切割功耗随刀片斜角的增大先减小后增大。验证试验表明：切割速度与刀片斜角均对其切割应力、单位面积切割功耗影响显著（P<0.05），与仿真试验结果吻合。研究结果可为谷子茎秆切割参数优化提供借鉴。

INTRODUCTION

Cutting is one of the necessary processes of crop mechanical harvesting. The cutter is one of the key parts of the harvester, and its performance parameters not only is a prerequisite for smooth progress of the harvester operation, but has great significance for reducing cutting force and energy *(Wang et al., 2017; Liu et al.,2018)*. Millet, a *graminaceous* plant, is mainly grown in the temperate and tropical regions of Eurasia, and it has gradually become an important crop for adjusting the structure of the planting industry and improving dietary habit with the improvement of people's living standards *(Annor, et al., 2017; Li, et al., 2018).* Nowadays, most researches mainly focus on the mechanical threshing, separating, cleaning and other mechanical harvesting issues to reduce grain loss *(Liang, et al., 2015)*.

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Imminently, due to the large diameter and high hardness of millet stalk, how to reduce the stalk cutting force and energy is an urgent problem to be solved under the background of energy conservation.

Our research group performed a quasi-static cutting mechanical test of millet stalk previously *(Zhang, et al., 2018)*. In order to obtain the cutting mechanical parameters more accurately, it is necessary to consider the dynamic cutting mechanical characteristics because of the faster cutting speed during mechanical harvesting. ANSYS/LS-DYNA is an explicit solution software that can solve highly nonlinear structural dynamic questions, and using it can greatly shorten the cycle of development *(Zhang, et al., 2010).* The mechanical model of cutting stalk belongs to a typical high-speed erosion model, and adopting ANSYS/LS-DYNA can clearly express the interaction between the stalk and the cutter to explore the failure form and the change laws of mechanical properties of the stalk under different cutting parameters. Most Scholars had used this software to simulate the cutting experiments of stalks such as Chinese Cabbage, sweet sorghum, corn and sugarcane, and the stalk failure stress during dynamic cutting was found (*Zhang, et al., 2010; Diao, et al., 2011; Huang, et al., 2011*). Many scholars also analysed the regular patterns of cutting mechanical properties of stalk with different cutting speeds and blade oblique angles *(Igathinathane, et al., 2010; Johnson, et al., 2012; Song, et al. 2015)*, but there are few studies about the dynamic cutting mechanical characteristics of millet stalk.

In this study, the material model of millet stalk and mechanical cutting simulation test based on ANSYS/LS-DYNA were carried out, and the simulation results were compared with the verification test based on the cutting test bench. The change rules of stress during mechanical cutting and the effect of cutting parameters on its properties were analysed. These results not only provide a modelling method for millet stalk, but supply a reference for optimization of cutting parameters of millet stalk.

MATERIALS AND METHODS

Sample preparation

The millet stalk was taken from the test field of millet planting in Taigu County, Shanxi Province, China (112º55′ E, 37º43′ N). After the stalks without lodging, diseases and pests were randomly taken back, the stalks were cut about 15 cm from the root. The moisture content (w.b.%) of the stalks were measured at 67.83% by the standard method *(ASABE, 2008)*. The cross section of millet stalk was similar to hollow ellipse, and the average length axis D_1, short axis D_2, and wall thickness T of stalks were about 12.50 mm, 7.75 mm, and 3.17 mm, respectively, as shown in Fig. 1.

Cutting model

In this study, the millet stalk was regarded as an elastomer, and the node load, node displacement, node speed, and node acceleration can be expressed by the following general dynamic equation in the process of analysing the elastomer *(Liu et al., 2018)*:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(T)\} \tag{1}$$

where: $[M]$ is the structural mass matrix; $[C]$ is the structural damping matrix; $[K]$ is the structural stiffness matrix; $\{X\}$ is the node position vector; $\{\dot{X}\}$ is the node velocity vector; $\{\ddot{X}\}$ is the node accelerated velocity vector; F is the load; T is the time.

Millet stalk is composed of epidermal tissue, basic tissue and vascular bundle *(Zhang et al., 2018).* The physical properties of millet stalk were shown in Table 1. Specifically, the wall thickness, density, elasticity modulus and shear modulus of epidermal tissue and inner tissue (basic tissue and vascular bundle) of stalks were measured in biomechanical test before this study *(Zhang, 2019)*, and the Poisson's ratio was taken from the references about agricultural material *(Ma et al., 2015).* According to the modelling method *(Cui et al., 2010)*, the stalk was simplified into a hollow elliptic cylinder with equal section, as shown in Fig. 1.

Table 1

The size and mechanical parameters of the cutting model

Material	Wall thickness [mm]	Density [g/cm^3]	Elasticity modulus [MPa]	Shear modulus [MPa]	Poission's ratio
Epidermal tissue	0.28	0.77	8.79×10^3	9.54×10^3	0.30
Inner tissue	2.89	0.72	4.93×10^3	3.71×10^3	0.30
Moving blade	/	7.85	1.98×10^5	7.86×10^4	0.35
Guard	/	7.30	1.51×10^5	6.10×10^4	0.25

The standard type II cutter (including the type II moving blade and the type IV guard) commonly used in harvester were selected, and its structural parameters and physical properties were determined according to the national standard of China *(China National standardizing committee, 2009)*.

The stalk cutting model is shown in Fig.2, and the mechanical parameters of the cutter are also shown in Table 1.

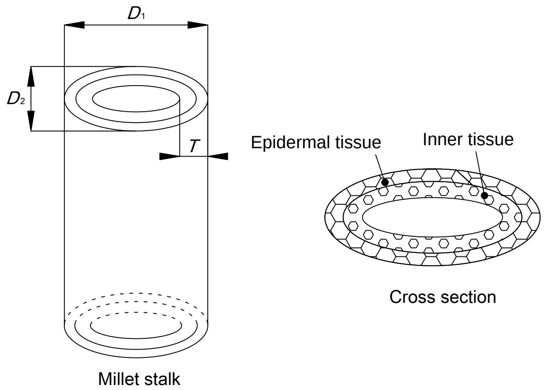


Fig. 1 Simplified stalk model

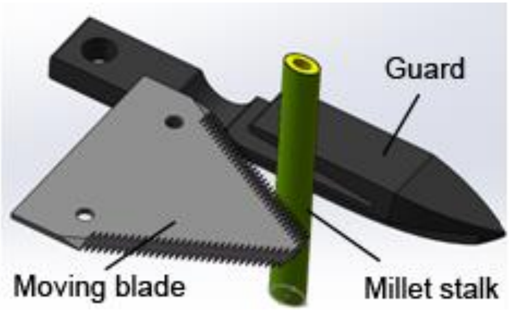


Fig. 2 Cutting model

Simulation test

HyperMesh Desktop 14.0 was adopted for pre-processing of the cutting model, including the following steps:

Cutting model meshing: Tetrahedral solid unit was selected to mesh the cutter and the stalk. The contact area of the cutter and the stalk and the non-contact area were meshed in turn, and the grid size of the contact area and the non-contact area were 2 mm and 5 mm, respectively. In this way, there were 2263, 8621, 58032 units for the moving blade, cutter and stalk, respectively.

Material parameter setting: The material parameters were determined according to the Table 1.

Contact condition and constraint condition setting: The contact forms of millet stalk with moving blade and guards were erosion contact and face contact, respectively， and the dynamic friction and static friction were 0.12 and 0.24, respectively *(Xue, 2018).* The moving blade was set to translational freedom in the cutting direction, and the guard and the bottom stalk were fully constrained.

Initial condition of simulation setting: In order to analyse the influence of cutting speed and blade oblique on mechanical properties of millet stalk, different cutting speed (0.5-1.5 m/s) and blade oblique angle (0°- 48°) were set in the simulation test. Meanwhile, the solution time and the simulation interval time were set to 0.04s and 0.0008s, respectively.

The pre-processing file was saved as a .k file, and then loaded into ANSYS / LS-DYNA to solve.

The stalk cutting energy and the reaction force received by the moving blade were recorded during the simulation cutting process, and the cutting stress and the unit area cutting energy were calculated by equation (2) and equation (4).

Verification test

The self-made cutting test bench was used to stalk cutting test (Fig.3). The cutting test bench is powered by a speed-regulating motor, and the slider-crank mechanism drives the moving blade to move in a straight line to complete the stalk cutting. The cutting force was measured by the force sensor, and the sensor signals were recorded by the TST5000 data acquisition instrument (Fig.4).

The motor speed can be controlled by the inverter to adjust the average cutting speed of the moving blade (0-2 m/s). The moving blade is provided with a central hole and an arc-shaped hole surrounding the central hole, so the angle of the moving blade can be adjusted from 0 ° to 48 ° (Fig.5).

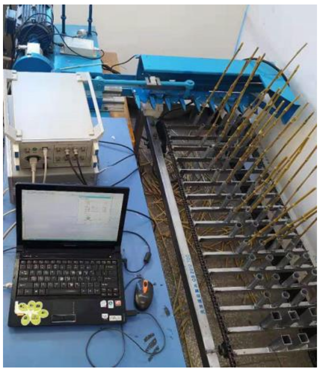


Fig. 3 - Cutting test bench

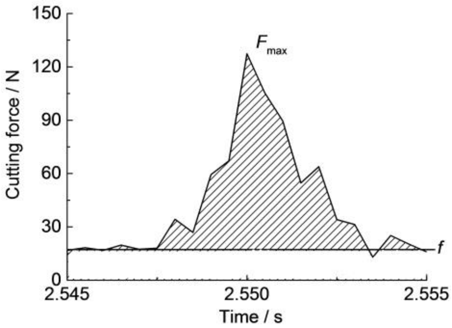


Fig. 4 - Curve of cutting force with time of millet stalk in verification test

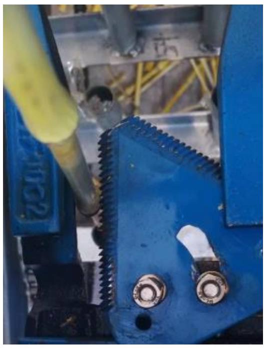


Fig. 5 - Adjustment of blade oblique angle

The stalk cutting force during the verification test was recorded by force sensor, and the cutting stress, cutting energy and the unit area cutting energy were calculated as follows:

$$\tau = \frac{F_{max} - f}{A} \tag{2}$$

$$W = \int_0^t (F \cdot v \cdot dt) - \int_0^t f \cdot v \cdot dt \tag{3}$$

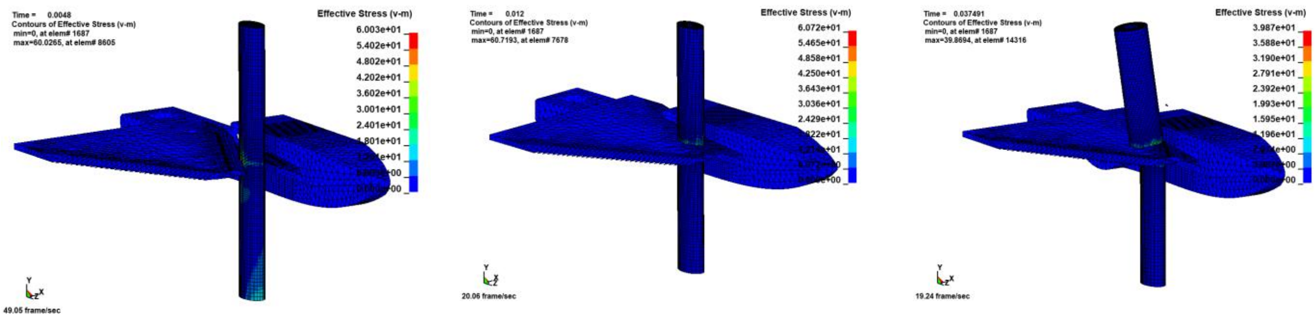
$$W_A = \frac{1000 \cdot W}{A} \tag{4}$$

where: τ is the cutting stress, [MPa]; A is the area of stalk cross section, [mm^2]; F_{max} is the maximum cutting force, [N]; f is the No-load resistance of moving blade in the verification test, [N]; F is the cutting force during the cutting test, [N]; W is the cutting energy, [J]; W_A is the unit area cutting energy, [mJ·mm^{-2}]; v is the average cutting speed, [m/s]; t is the cutting time, [s].

RESULTS

Stress distribution of millet stalk during cutting

The stress-strain cloud diagram of millet stalk from simulation test is shown in Fig.6. When the cutting speed was 1 m/s and the blade oblique was 30°, the stalk was squeezed first, and the maximum Von Mises stress of stalk at the contact point with the moving blade increased rapidly to 60.03 MPa. This is due to the tougher epidermal tissue of the millet stalk, and the moving blade had a certain impact force, resulting in Von Mises stress rising rapidly. Then the moving blade cut into the stalk, and the Von Mises stress changed dynamically, and the maximum Von Mises stress was 60.72 MPa. After cutting, the stalk was cut off and there was a certain residual stress of stalk, and the maximum Von Mises stress decreased to 39.87 MPa. Similar rules were found in other simulation tests at different cutting speeds and blade oblique angles.



Before cutting During cutting After cutting

Fig. 6 - Stress and strain cloud diagram of the millet stalk during cutting

The variations of the cutting force, the cutting energy of stalk epidermal tissue and the inner tissue were shown in Fig.7, Fig.8 and Fig.9, respectively. In the cutting process, the cutting force increased intermittently until the stalk was cut off, the cutting force dropped to 0 N.

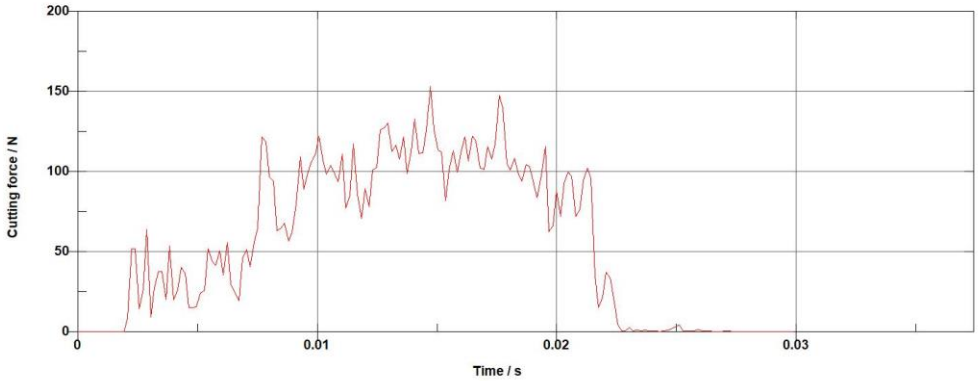


Fig. 7 - Curve of cutting force with time of millet stalk in simulation test

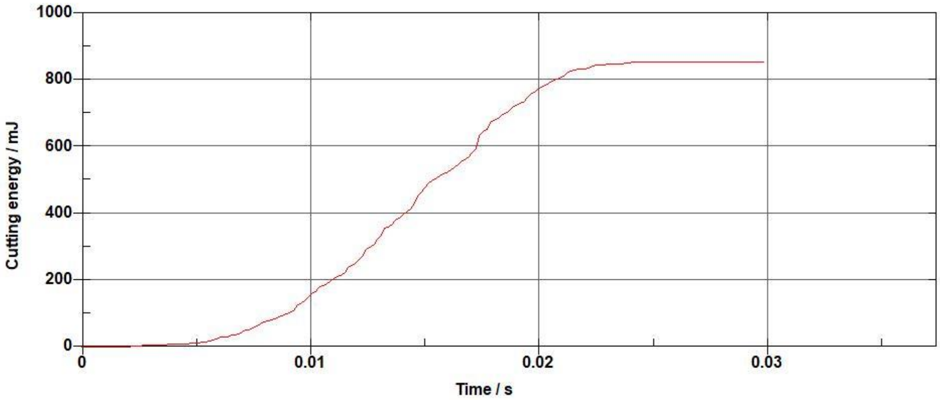


Fig. 8 - Curve of cutting energy with time of epidermal tissue of stalk in simulation test

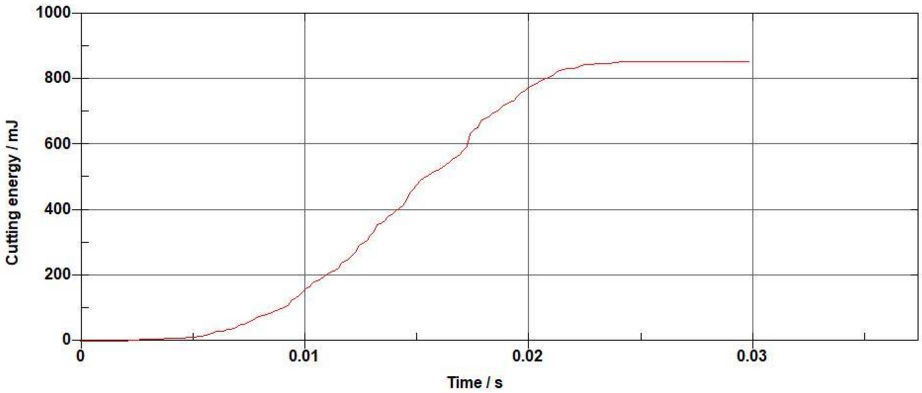


Fig. 9 - Curve of cutting energy with time of inner tissue of stalk in simulation test

The cutting energy of the epidermal tissue and inner tissue of stalk increased first and then presented a stable change trend. When the cutting speed was 1 m/s and the blade oblique angle was 30°, the maximum cutting force and the whole cutting energy (cutting energy of epidermal tissue and inner tissue) were 153.02 N and 1.07 J, respectively. The cutting energy of epidermal tissue and inner tissue of stalk were 0.86 J and 0.21J, respectively. Obviously, the epidermal tissue is stronger than the inner tissue of stalk, and similar rules in other simulation tests at different cutting speeds and blade oblique angles.

Effect of cutting speed on mechanical cutting characteristics of millet stalk

Simulation tests were conducted at five average cutting speeds of 0.5, 0.75, 1.0, 1.25 and 1.5 m/s. The variations of cutting stress and unit area cutting energy of stalk are shown in Fig.10. From Fig.10, we can find that the cutting stress and unit area cutting energy of stalk showed a trend of first decrease and then steady change with increasing average cutting speed.

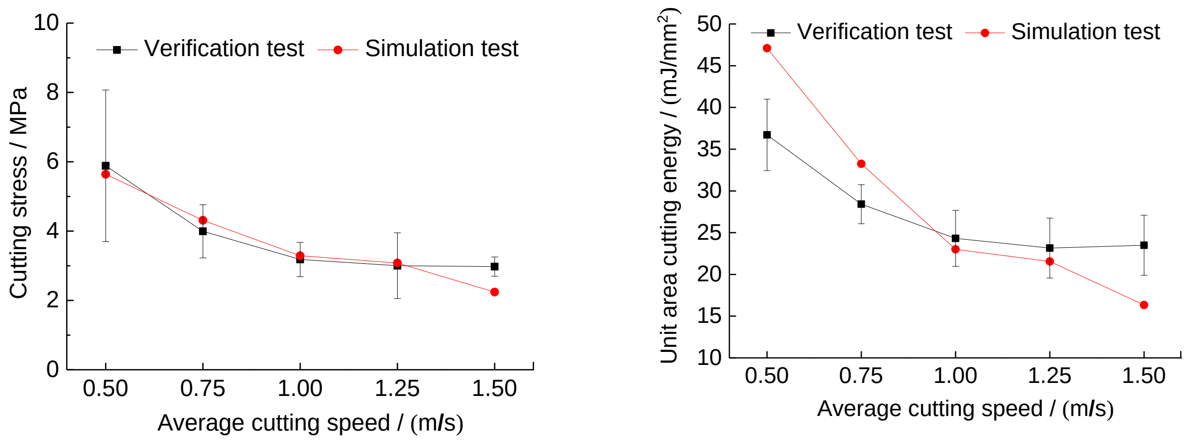


Fig. 10 - Variation of cutting mechanical properties with cutting speed

The reason was that the cutting process was divided into extrusion process and cutting process. When the cutting speed was slow, the stalk had a compression deformation under the action of cutter, but the time to transfer the stalk compression deformation gradually decreased with the increasing cutting speed. As a result, the amount of compression deformation does not change significantly, that is, the moving blade can easily cut into the stalk to complete the cutting at a higher speed. These results were consistent with the cutting tests previously mentioned by *Li et al.* (2011) and *Song et al.* (2015).

Verification tests at different cutting speeds were also carried out in this study, and similar rulers were found in verification tests. When the average cutting speed was 0.5-1 m/s, the cutting stress and the unit area cutting energy of stalk decreased significantly (P<0.05), but the cutting mechanical characteristics did not change significantly when the average cutting speed was 1-1.5 m/s (P> 0.05). The cutting stress and unit area cutting energy were the smallest when the average cutting speed was about 1 m/s. Therefore, the cutting simulation model established in this study was effective and could be used to reflect the cutting mechanical properties of millet stalk to a certain extent.

Effect of blade oblique angle on mechanical cutting characteristics of millet stalk

Simulation tests were conducted at five blade oblique angles of 0°, 12°, 24°, 36° and 48°. The variations of cutting stress and unit area cutting energy of stalk are shown in Fig.11. As can be seen, the cutting stress decreased with the increasing blade oblique angle, but the unit area cutting energy decreased first and then increased with the increasing blade oblique angle. These results were also consistent with studies by *Mathanker et al*. (2015) and *Song et al.* (2015). The reason can be attributed to the fact that the stalk was firstly clamped and fixed by the cutter, and the blade oblique played the role of sliding cutting the stalk. The actual wedge angle of moving blade is decreased with increasing blade oblique angle when sliding cutting the stalk *(Pang et al., 1982).* Thus, the normal force used to cut stalk is reduced, and the cutting stress and unit area cutting energy decreased. However, the relative distance between the stalk and the moving blade increased when the blade oblique angle was too large. So, the cutting energy is not only used to cut the stalk, but also for the friction power consumption between the stalk and the moving blade, leading to an increase in unit area cutting energy of stalk.

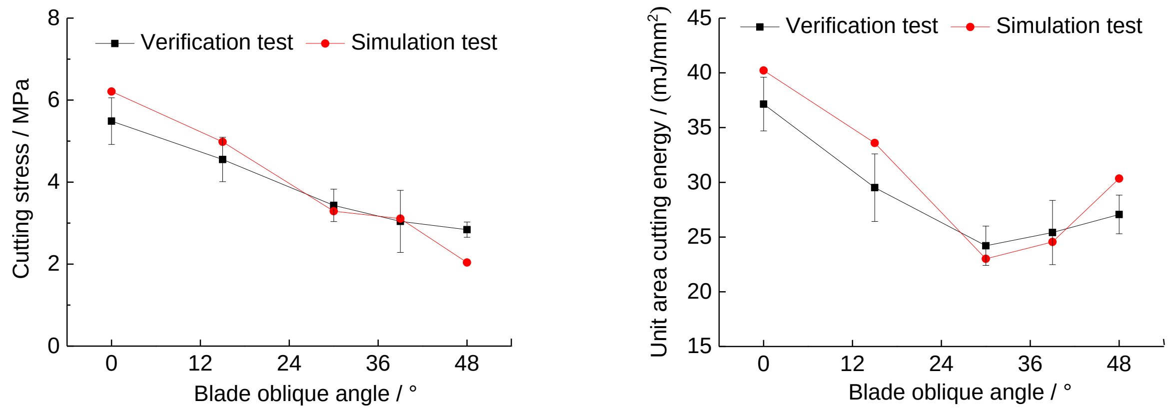


Fig. 11 - Variation of cutting mechanical properties with blade oblique angle

Verification tests at different blade oblique angle were also carried out in this study, and similar rulers were found in verification tests. Multiple comparisons of the mean values showed that the blade oblique angle had a significant effect on the cutting stress and the unit area cutting energy of stalk (P> 0.05), and the unit area cutting energy was smallest when the blade oblique angle was about 30°. These results were different from the previous quasi-static cutting test results *(Zhang et al., 2018)*, which is caused by high-speed cutting, and the high-speed cutting was much closer to the actual working conditions of harvest.

CONCLUSIONS

The simulation tests and verification tests of dynamic cutting of millet stalk were carried out, and the following conclusions were obtained:

(1) Dynamic cutting process of millet stalk could be divided into extrusion process and cutting process, and the maximum Von Mises stress was concentrated on the contact point of the stalk and the moving blade.

(2) The cutting energy of stalk epidermal tissue was greater than that of inner tissue.

(3) The verification test results were consistent with those of the simulation test. The cutting speed and the blade oblique angle had significant effects on the cutting mechanical properties (P < 0.05). When the average cutting speed was 0.5-1.5 m/s, the cutting stress and the unit area cutting energy decreased first and changed steadily with the increasing cutting speed. When the blade oblique angle was 0°- 48°, the cutting stress decreased with increasing blade oblique angle, while the unit area cutting energy decreased first and then increased.

(4) The average cutting speed and the blade oblique angle suitable for millet stalk dynamic cutting were about 1 m/s and 30°, respectively.

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