STUDY ON THE RAPE POD SHATTER RESISTANCE SUITABLE FOR LOW-LOSS HARVESTING OF HARVESTER REEL

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适宜收获机拨禾轮低损失收获的油菜角果抗裂角性研究

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ABSTRACT

During the mechanical harvesting of rapeseed, the impact of the rotating reel tine on rape can easily cause the pods to burst and seeds drop. However, the specific size of the pod shatter resistance suitable for mechanical harvesting is unsure. In this paper the impact force on the rape was analysed through the measurement and wireless transmission of stress change of the tine. A two-degree-of-freedom (2-DOF) collision tester of pod resistance for field testing was used. The results of the shatter resistance index (SRI) under 2-DOF method and the cracking force under ripping method were compared. According to the results of SRI, cracking force and tine impact force, the expected field SRI was determined. The results show that the tine impact forces at the low reel speed of 18 revs min^{-1} was 1.76 N. The 2-DOF method results are reliable and the SRI is significantly correlated with the cracking force. The SRI should be over 0.576 to be greater than the impact force under the low reel speed, however, only 14.8% of the tested varieties could satisfy. It indicates the resistance of the commercial varieties is generally poor and need to strengthen.

摘要

油菜机械联合收获中，拨禾轮弹齿对油菜造成的打击很容易使角果炸裂和种子掉落，但是适于机械收获的角果抗裂角性具体大小一直是未知的。本文通过对收获过程中弹齿应力变化的测量和无线传输，分析了其对油菜的碰撞力；使用便于田间检测角果抗裂角性的二自由度随机碰撞仪，并将该方法测得的抗裂角指数（SRI）与拉裂法下的开裂力结果进行了比较；根据SRI、开裂力和碰撞力结果，得到机械收获期望的SRI大小。结果表示，在拨禾轮低速旋转18 rev min^{-1}下，对应的弹齿碰撞力为1.76N；SRI结果与开裂力间有显著的相关性，说明两自由度碰撞方法结果可靠；满足拨禾轮18 rev min^{-1}下收获要求的角果抗裂角指数应大于0.576，所测品种中仅有14.8%满足此要求，这说明目前市场油菜品种的抗裂角性还是普遍较差，需加强品种的选育。

INTRODUCTION

Rapeseed (*Brassica napus*), which is an important oil crop, is an essential raw material in not only edible but also industrial applications (*Btluri et al.,* 2013*; Delgado et al., 2018; Shubert, 2018*). However, rape pods have the characteristic of easy cracking, that is, the pods in the mature stage are easy to crack under external forces, which lead to large losses of mechanized harvesting, especially the header losses that can account for more than half of the total losses (*Shim et al.,* 2017*; Bruce et al., 2002; Cavalieri et al., 2014*). The main reason for the above problem is the mismatch between the rape combine harvester requirement and the pod shatter resistance. When the rape combine harvester is working, the reel placed horizontally in front of the header is the first component that contacts with the rape directly. Its rotary movement cans easily attacks the pod burst quickly and causes extensive seed falling losses, which is the main source of the header losses (*Cavalieri et al.,* 2016*; Pari et al., 2012*).

In order to reduce the losses and screen the varieties with strong pods that are suitable for mechanized harvesting, many researches have been done on the evaluation methods of pod shatter resistance. These methods can be divided into two categories in terms of testing principle.

One is to measure the magnitude of bending moment or the ripping force when the pod is bent or cantilevered tearing by using an experimental device indoor, including the ripping method developed (*Hobson et al., 2002*), and the ripping method has been improved (*Kadkol et al., 1985*). In addition, a three-point bending fracturing method has also been designed (*Tan et al., 2006*).

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However, these methods were carried out under the static or quasi-static conditions without considering the pod resistance under dynamic harvesting conditions. The other is to adopt the principle of random collision, which applies the collision between metal balls and pods to test the shatter resistance. This principle was first proposed by *(Morgan et al., 1998*), which takes into account the dynamic conditions and has a good repeatability of test results. Therefore, this principle is generally accepted by researchers, including the (*Morgan et al., 2000*) and (*Summers et al., 2003*), all applied this principle and improved the test method. However, all of them were tested under laboratory conditions, and the pod shatter resistance of varieties can only be roughly divided into two categories, namely, cracking resistance and easy fragile. It is impossible to know the specific value of pod shatter resistance that meets the requirements of mechanical harvesting. The main reason for the above phenomenon is that few scholars have researched the impact force of the harvester reel on the rapeseed pod in the actual harvesting process, the relationship between the impact force and pod resistance has not been established.

Considering the above mentioned problems, from the perspective of integrating agricultural machinery and agronomy, this paper analysed and measured the impact force between the combine harvester and the rape in the working process. In addition, a two-degree-of-freedom (2-DOF) random collision method was used. The results of ripping method and the 2-DOF method were analysed and compared, and combined with the tested impact force of the reel, the expected value of the pod shatter resistance for the mechanized harvesting was determined. Moreover, the pod resistance of typical rape varieties was investigated, and resistance varieties for harvesting were screened.

MATERIALS AND METHODS

2.1 Working principle and movement of harvester reel

The main function of the reel is to push the crops to be harvested towards the cutter, and then cooperate with the cutter to cut the stalks and push the cut crops to the auger to avoid stalk accumulation on the cutter and header (*Peng et al, 2013; Moses et al, 2012*). The trajectory analysis of the reel is shown in Figure 1. The rectangular coordinate system is established as shown in the figure. The machine's forward direction is forward right, and the reel rotates counterclockwise, the trajectory equation of a certain point A_0 on the reel can be expressed as:

$$\begin{cases} x = V_m + R\cos\omega t \\ y = H - R\sin\omega t + h \end{cases} \tag{1}$$

Where, V_m is the forward speed of harvester, m s^{-1}; t is the working time of reel, s; R is the reel radius, m; ω is reel angular speed, rad s^{-1}, H is the vertical distance between horizontal central axis of reel and main cutter, m; h is the cutting height of the main cutter, m.

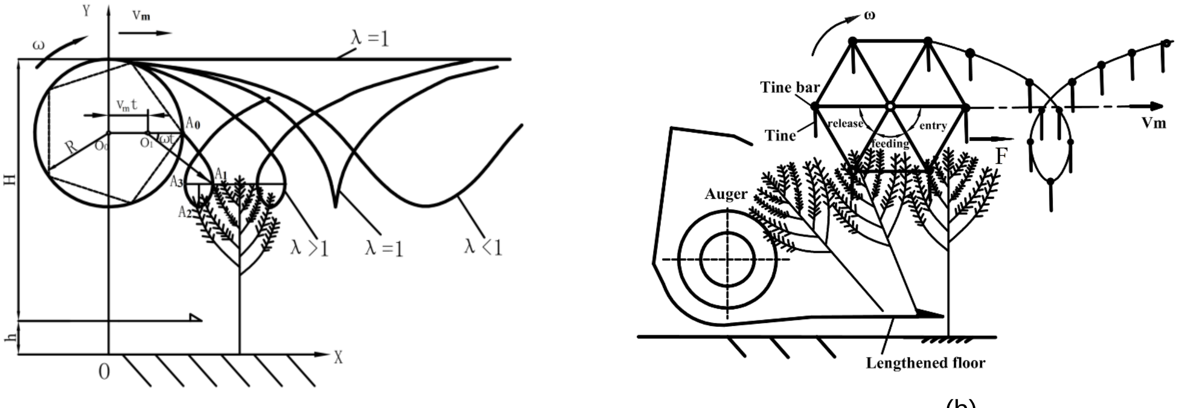
The horizontal and vertical speeds of the reel can be obtained by deriving equation (2):

$$\begin{cases} V_x = \dfrac{d_x}{d_t} = -R\omega sin\omega t + V_m \\ V_y = \dfrac{d_y}{d_t} = -R\omega\cos\omega t \end{cases} \tag{2}$$

Suppose the circumferential speed of the reel is V_b, the combine forward speed is V_m and the reel speed ratio is $\lambda = V_b / V_m$. Different λ values have different forms of reel trajectories as shown in Fig. 1 (a). When $\lambda = 0$, the trajectory of the reel is a straight line, when $0 < \lambda < 1$, the trajectory is a curtate cycloid with no buckle and when $\lambda > 1$, the trajectory is a prolate cycloid with a buckle ring. Because the reel needs to support the crops to be cut into the header, the reel motion should have a backward horizontal velocity. Only when $\lambda > 1$, in the lower part of the buckle in the trajectory curve, that is, below the longest horizontal chord A_1A_3, the point on the reel has a backward horizontal speed, which can meet the working requirements. When the reel is working, the horizontal position point A_0 moves to point A_1, its absolute moving speed direction is vertical downward without horizontal sub-velocity V_x. At this condition, the impact of the reel tine is the least when it enters the crop, so theoretically it is required that it is the best entry point for the reel.

In the harvesting process of the combine, the operation process of the reel tine is shown in Fig. 1(b). It mainly includes three stages. The first is entering the crop, whose function is to support the crop to be cut; the second is the feeding, which pushes the cut crops into the auger; and the last is the releasing stage, the tine leaves the crop to prepare for the next round of work.

Except for the three stages, the rest of the reel's rotation cycle is empty stroke without any contact with the crop. Among them, the stage of entry is the main reason for the loss of the header. The impact force direction of the tine is shown as F in the graph. Because the reel tines are a little outside of the header bottom plate at this stage, this leads to the burst pods and seeds cannot fall inside the header. Therefore, the study of the impact force between the reel tine and the rape pod at the early stage of entering the crop is the key to reduce the loss.



(a)

(b)

Fig. 1 - Analysis of the trajectory and working process of the reel
(a) Theoretical analysis of the trajectory of reel;
(b) Schematic diagram of the working process of the harvester reel.

2.2 Tests of the impact force of the reel tine on rape pod

2.2.1 Static calibration test of force on the tine

The reel tine that direct contact with the pod was selected as the monitoring object, by collecting the signal change of the force on the tine calculating the impact force on the pod. The DH5905 dynamic signal acquisition and analysis system (Donghua Testing Co., Ltd., Taizhou, China) is selected for testing. Since the reel tine is slender cylindrical, the surface of the tine needs to be ground flat when attaching the strain gauges. The strain gauge is connected in a half bridge circuit (two working pieces), which is suitable for measuring bending strain. The contact lead of strain gauge was connected with the acquisition module of DH5905 strain test system, and the static calibration of strain test part was carried out, and the test device is shown in Fig. 2. Since the initial stage of entering the crop is the main stage that causes the header loss, at this time the collision position between the reel tine and the pod is at the tine end mainly, thus, it was selected as the loaded position on the calibration test bench. In the test, different weights were added sequentially on the tine end. The average value of the stabilized stress collected in the computer was recorded as the tine stress value; each group was repeated 3 times. The least square method was used to fit the data measured in the calibration test.

The proportional coefficient *b* and the intercept *a* in the regression equation is obtained by formula (3) and (4).

$$b = \frac{\sum_{i=1}^{n}(T_i - \bar{T})(U_i - \bar{U})}{\sum_{i=1}^{n}(T_i - \bar{T})^2} \tag{3}$$

$$a = \bar{y} - b\bar{x} \tag{4}$$

where:

b is proportional coefficient, MPa N^{-1};

T_i is the force loaded at the *i*-th time, N;

U_i is the corresponding output stress of the *i*-th load acquisition module, MPa;

$\bar{T}$ is the arithmetic mean of loading force for all times, N;

$\bar{U}$ is the arithmetic mean value of the corresponding output stress of all load times acquisition modules, MPa;

n is all load times for a set of test.

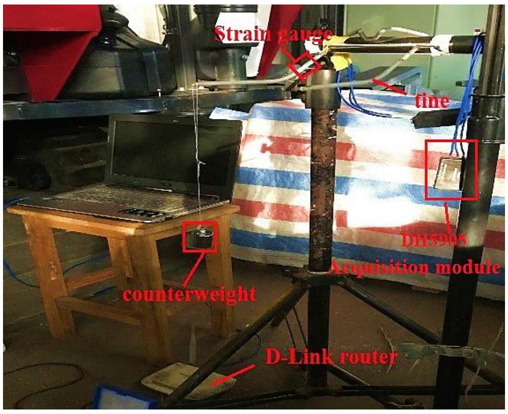


Fig. 2 - Static calibration test bench for force and stress of reel tine

2.2.2 Field experiment on the impact force of the tine

The field test of the impact force of the reel tine on the pod in the working state of the combine harvester was conducted in Dafeng farm in Yancheng City, Jiangsu Province, China in June 2018. The harvest rape cultivar was Zheyou 51, the yield was 2258 kg ha^{-1}, and the average plant height was 1186 mm. The same strain gauge connection method with the indoor calibration was used in the field test. The strain gauges are attached to the front and back sides of the tine of the rape combine, and the DH5905 dynamic signal acquisition device was fixed on the harvesting frame. In the experiment, as the height of the harvested rape plant is constant in the field, the reel height and the horizontal displacement relative to the cutter were set as 1000 mm and 300mm respectively. The stresses of the tine under the reel speeds of 18, 24 and 30 rev min^{-1} were tested with three replicates and the frequency of stress acquisition was 2 kHz.

2.3 Comparative experiments of pod shatter resistance in different methods

2.3.1 Ripping method

Fig. 3 - Measurement of the rape pod ripping force using a texture analyser

Ripping method is an available method that can directly quantitatively measure the force of separate layer cracking in the lab. The Texture analyser (TA.XT Plus, Stable Micro Systems, UK) was used to measure the force. The test operation is shown in Fig. 3. Before testing, the pod was tangled at a distance of 25mm from the peduncle with a wire to ensure that the arm of force was consistent for different pods ripping. A L-hook was used to hook the pod stalk and was pulled by the texture probe at a speed of 10 mm/min, the force of the probe was recorded on the computer in real time. During the test, the tensile force increased continuously before the pod cracking, and when the force reached a certain value, it decreased instantly, and the peak value was the pod cracking resistance force. The experiment was repeated 5 times for each variety.

2.3.2 Two-degree-of-freedom (2-DOF) random collision method

The object of mechanical harvesting is the natural growing pods in the field; in order to reduce the influence of human interference on the pod characteristic and reflect the resistance exactly, it is necessary to develop a method and an instrument that are convenient for field testing. To solve the above problem, a two-degree-of-freedom collision tester was designed by our research team, as shown in Fig. 4 (*Qing et al., 2019*).

The principle of random collision was applied in this method, a two-stage motion mechanism was proposed. The first-level is reciprocating vibration mechanism, and the second-level is swing mechanism. The controller can separately control the speed and working time of motor *1* and motor *2*, and set different motion frequencies. During the test, 20 intact pods of the same variety and maturity and 12 steel balls with a diameter of 13mm were placed in the material box at the same time. The stepper motor controller would stop automatically every 1min. Then the broken pods were taken out and their number was recorded. Repeat the above operation no more than 10 times, and calculate the pod shatter resistance according to formulas (5) and (6). Each group of tests was repeated three times, and the formula of pod shatter resistance index is as follows:

$$SI = \frac{\sum_{i=1}^{10} x_i (10 - i + 1)}{n_1 \cdot n_2} \tag{5}$$

$$SRI = 1 - SI \tag{6}$$

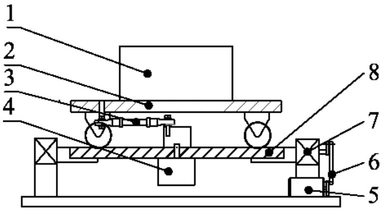
where: SI is the pod shatter index;

x_i is the number of broken pods at time i;

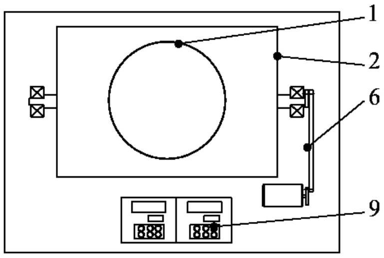
n_1 is the total number of pods, which is 20 here;

n_2 is the specified total number of collision repetitions, which is 10 here;

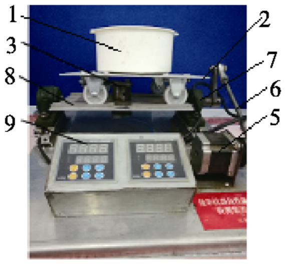
SRI is pod shatter resistance index.



a. Front view



b. Top view



c. Physical map

Fig. 4 - Structure and physical diagram of the 2-degree-of-freedom collision tester

1. Material box; 2. Upper plate; 3. Crank slide mechanism; 4. Motor 2; 5. Motor 1; 6. Crank rocker mechanism; 7. Bearing; 8. Lower plate; and 9. Controller.

2.3.3 Test materials and program

A total of 15 varieties that related to the pod resistance were planted in the Experimental field of Agricultural Equipment Engineering College of Jiangsu University. In the two years of 2018 and 2019, during the yellow ripening period of rapeseed in May, 5 plants of the same growth and colour of plants were selected from each variety randomly. The main inflorescences of the plants were cut and marked, and then were placed in a room at 25°C under constant temperature and humidity to dry naturally for 25 days to ensure that the moisture content of different varieties was consistent. After drying, the intact pods with the same growth rate and without diseases and insect pests in the middle of the main inflorescence were cut for experiment. Then the shatter resistance of these pods was tested by the ripping method and 2-DOF random collision method.

The test results of the two methods were compared and analysed, and the linear relationship between the cracking force and the SRI was found. Combined with the test results of the impact force between the reel tine and the rape during the field mechanized harvest, the range of the SRI suitable for mechanized harvest was obtained. In addition, the 2-DOF tester was moved to the field, and 12 rape varieties were randomly selected from the experimental field of Jiangsu Academy of Agricultural Sciences on May 25, 2018. The pod shatter resistance of varieties on the market was investigated for surveying whether the field pod resistance meets the needs of mechanical harvesting.

RESULTS

3.1 Impact force of reel tine on the rape during harvesting

After processing the test data collected by the calibration, it is found that there is a significant linear relationship between the internal stress signal and the load on the tine. The load size and the corresponding average stress measured in the test are shown in Table 1. According to the formula (3) and (4), the scale coefficient *b* of the tine calibration is 0.0797, and the intercept *a* is 0.042. Therefore, the relationship model between the force *y* and the internal stress *x* of the tine collected by the system is obtained as follows:

$$y=0.0797x+0.042\ (R^2=0.993) \tag{7}$$

Table 1

Results of the load size and the average stress measured in the static calibration test of the reel tine

Load (N)	0.1	0.2	0.3	0.4	0.5	0.75	1.0	2.0
Measured stress (MPa)	1.126	2.261	3.275	4.687	5.532	8.278	11.531	24.942

The operating parameters of the highest harvesting efficiency with the reel speed of 30 rev min^{-1} were taken as a typical example to analyse the field test results in detail. Fig. 5 shows the measured stress change curve of the reel tine at the reel speed of 30 rev min^{-1}. Fig. 5(a) is the general diagram of the tine stress from the harvester start up; it can be seen from it that the stress variation of the whole curve can be divided into three areas A, B and C.

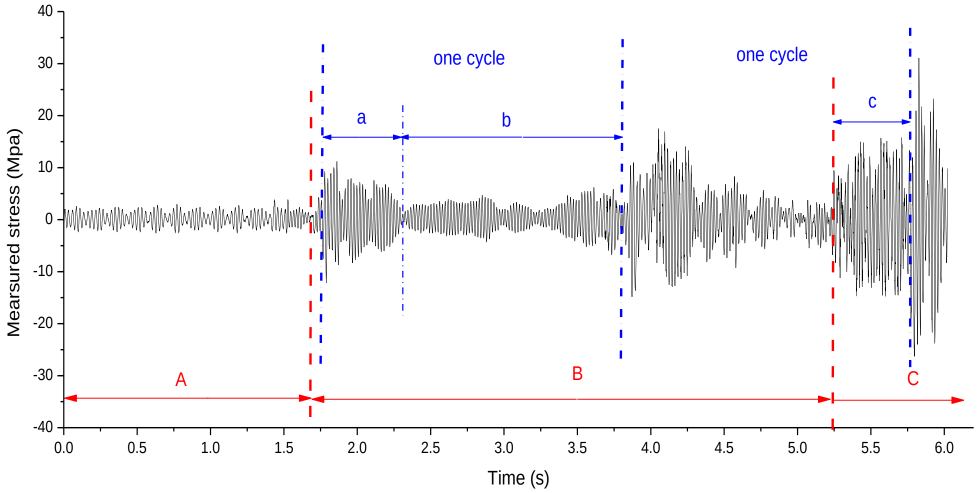
The amplitude of the stress curve change in the period of ‘A’ is very small and has certain regularity, generally not more than 5 MPa. During this period, the machine had just started up without moving, and the reel had not been running, so the tine stress change was caused by machine vibration.

At the beginning of period ‘B’, the tine stress increased instantaneously, and the overall showed a cyclical change trend of first increasing and then decreasing. Because during this stage, the harvester stayed at the edge of the field and had not yet moved forward, but the reel had started to operate, when the tine hit the rape on the edge of the field, the stress measured increases instantly, and when the tine separated from the rape plant, the stress began to decrease. During the period of ‘C’, the stress increased sharply, and it was found that the stress in empty stroke stage ‘C’ was significantly higher than that of ‘B’ at the same stage. This is because of vibration increase caused by uneven field when the machine started to go forward for harvesting, which means that the machine walking has a great influence on the tine stress and the vibration will significantly increase the impact force. In order to judge the cycle easily in the curve, the moment of the stress value increased instantaneously, that is the moment when the tine attacked the pod, which was selected as the starting point of the cycle. In the graph, the two blue dot sliding lines are the tine stress changes of one revolution from the contact, among them, the period ‘a’ is the working stroke of contact with the rape, and the period ‘b’ is the empty stroke period without contact.

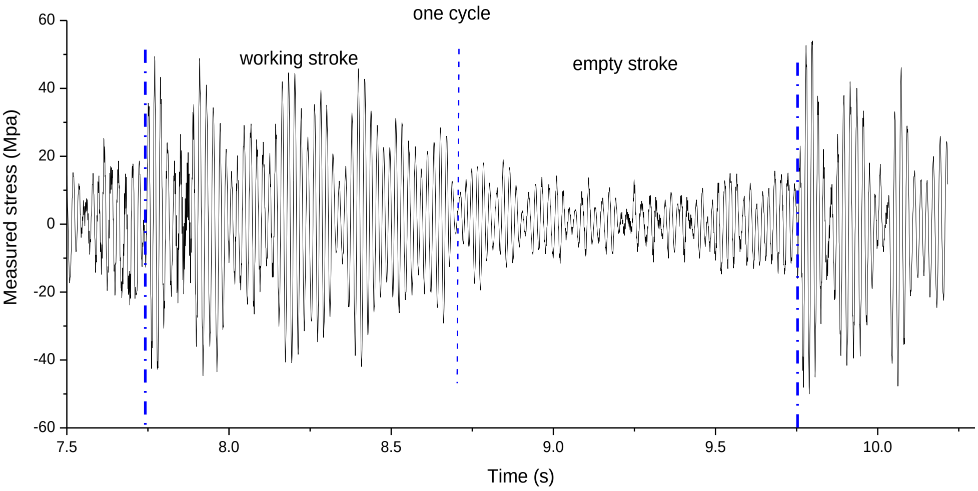
Fig. 5(b) shows a complete cycle of stress variation collected after the harvesting operation is stable. It can be seen that the stress curve fluctuates greatly due to the uneven ground, machine vibration and impact force. In the design of the rape harvester, in order to reduce the seed falling loss, the harvester bottom plate will be lengthened. For the later stage of entering, the feeding and the releasing stages, the burst pods will directly fall into the inside of the header, so the impact force causing the header loss is only affected by the early stage of feeding. In the calculation of the impact force, the maximum stress within 0.1s after the start of one cycle of rotation was selected as the effective conversion stress value. The stress values of three cycles were randomly selected for each test and averaged, with three replicates for each group of parameters, and then the impact force was calculated according to formula (7).

The results of converted contact force were showed in Table 2. This illustrates that the reel speed has a significant influence on the force.

Theoretically, the pod cracking resistance force should be greater than the tine impact force, which can reduce the pod burst and decrease the header loss. Therefore, the pod resistance force would be best greater than 3.85 N and at least over 1.76 N for the selection of rape varieties that are suitable for mechanized harvesting.



(a)



(b)

Fig. 5 - The measured stress change curve of the reel tine with the reel speed of 30 rev min^{-1}

(a) General diagram of the tine stress collected during the harvesting period from the harvester start up;

(b) The tine stress variation collected after the harvesting operation.

Table 2

Machine operation parameters and conversion results of the tine impact force in field test

Reel speed (rev min^{-1})	**Reel height (mm)**	**Harvester forward speed (m s^{-1})**	**Reel speed ratio λ**	**Converted tine contact force (N)**
18	1000	0.6	1.41	1.76
24	1000	0.8	1.41	2.82
30	1000	1.0	1.41	3.85

3.2 Comparison results of pod shatter resistance by two methods

The results of pod shatter resistance of different varieties by ripping method and 2-DOF collision method are shown in Fig. 6. There was a significant correlation between the two results with the Pearson correlation coefficient being 0.937 ($P < 0.01$). This reflects that the test results of 2-DOF collision method are reliable. The results of pod resistance of other varieties under the two methods were similar in two years, therefore, it is concluded that the genotype is the main factor to determine the pod resistance. Among them, C6009 had the strongest pod with the highest shatter resistance.

A linear regression model was established for the data results of the two methods, and the following relationship was found between the cracking force resistance F and the SRI:

$$F=2.186 \cdot SRI+0.501 \ (R^2=0.890,\ P<0.001) \quad (8)$$

Two varieties 15w2130-20 and F17W82-n747 are used for verification test. The SRI measured by the test were 0.275 and 0.358 respectively, and the ripping force was 0.975 N and 1.135 N respectively. The results are similar to the theoretical values 1.102 N and 1.284 N, which justifies that the model is reliable. The tine impact force at the reel speed of 18 rev min^{-1} is 1.76 N. In order to reduce the header loss caused by reel tine attack, the pod cracking resistance force should be greater than the value theoretically. According to the model relationship, it can be concluded that the pod shatter resistance index (SRI) should be greater than 0.576 under the same resistance.

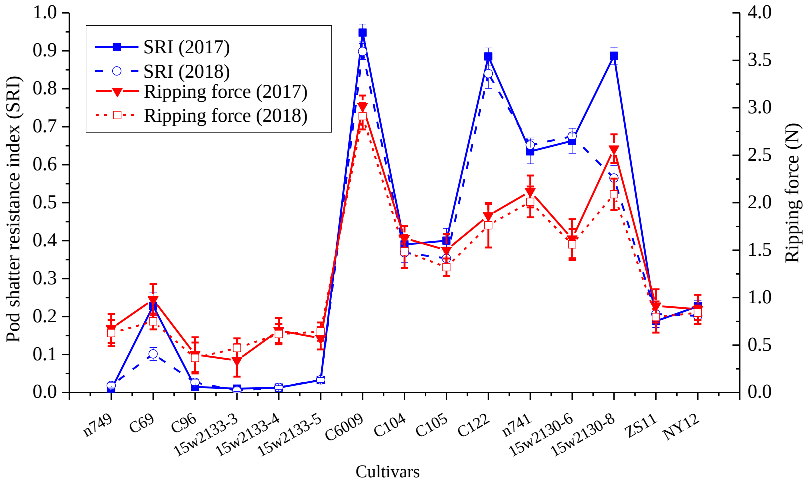


Fig. 6- Results of pod shatter resistance of different varieties by ripping method and 2-DOF collision method

3.3 Investigation results of rape pod resistance planted in the field

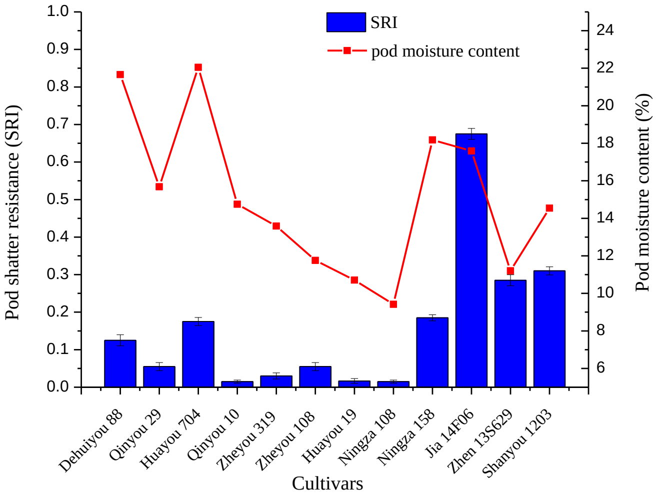


Fig. 7 - The investigation results of pod shatter resistance of the field-grown rape varieties

The investigation results on pod shatter resistance of twelve randomly selected field-grown rape varieties are shown in Fig. 7. During the test, the Sfy-20 infrared rapid moisture tester (Haibin Instrument Co., Ltd., Shenzhen, China) was used to measure the moisture content of all varieties of pods in the field site test. The variation range of the SRI of all varieties was 0.015-0.675, and the water content of pod varied from 11.20% to 22.05%. Among them, the variety with the strongest resistance was Jia14F06. In addition, it was found that the pod moisture content was not the most important factor influencing the resistance. For example, Huayou704 had the highest moisture content of 22.05%, but its pod resistance index was not the largest, only 0.175. This indicates that the genotype of rapeseed has a greater influence on the resistance, and it is reliable to select varieties with high shatter resistance to reduce the harvest loss.

3.4 Current varieties situation of rape pod shatter resistance

A total of 27 rape varieties measured in all tests were classified by the value of SRI, and the distribution of the varieties number in different SRI ranges are shown in Fig. 8.

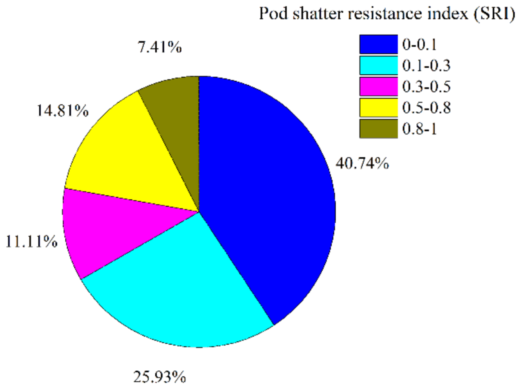


Fig. 8 - Distribution diagram of the number of rape varieties in different pod shatter resistance index (SRI) ranges

It can be seen from the distribution pie chart that the number with the SRI < 0.1 accounted for the largest proportion of 40.74 %, and there are 11 varieties in total, which are very easy to burst and cause large losses in the harvesting process. There are only 6 rape varieties with the SRI greater than 0.5, in which only 4 varieties can meet the required SRI of 0.576 of the low reel speed, accounting for 14.8%. There is no cracking resistance force in the tested varieties that can be greater than the impact force at the reel speed of 30 rev min^{-1}. That indicates that the crack resistance of rapeseed varieties in the market is generally poor, which doesn't not satisfy the harvesting requirement of combine harvesters.

CONCLUSIONS

When rape pods have poor shatter resistance, the impact of the rotation movement of the reel on rape will make the pod crack rapidly and cause the drop loss of rapeseed, which is the main reasons for header loss. In this paper, the signal acquisition and analysis of the internal stress caused by the impact between the tine and the rape under different reel rotation speeds of 18, 24, and 30 rev min^{-1} during the mechanical harvesting was carried out, the corresponding sizes being 1.76, 2.82 and 3.85 N.

The developed two-degree-of-freedom (2-DOF) collision tester has the advantages of easy to move, simple operation, and can be used for field test of pod shatter resistance, which can reflect the true characteristics of the pod grown in the field object during the harvesting period and be more conducive to screen reliable and suitable rape varieties for mechanical harvesting. The expected SRI value of 0.576 that meets the harvesting requirements of the reel at low speed was determined. There was no variety of all the tested pods in this paper whose pod resistance could satisfy the requirement of the tine impact force at the reel high-speed, and only 14.8% of the tested varieties had it greater than the standard. Therefore, the current commercial and researched rape varieties are generally poor in pod resistance, which does not match the harvesting requirements of combine harvesters.

For the rape pods of the same variety, the higher the water content, the better the cracking resistance. Therefore, for the varieties with stronger resistance, it is recommended to continuously test the pod resistance during their maturity stage and choose the appropriate harvesting time to improve the pod resistance to meet the harvesting requirements. However, the moisture content of pods during harvesting should not be too high to avoid excessive load and loss in the threshing and cleaning process. On the other hand, it is suggested to improve the reel tine material and develop the flexible tine, increasing the use of flexible materials to reduce the impact force of the tine. This study provides a reliable screening standard for selecting rape varieties suitable for mechanical harvesting, and promotes low-loss rapeseed harvesting.

ACKNOWLEDGEMENT

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