STUDY ON THE CHARACTERISTICS AND DISTRIBUTION OF DAMAGE RESISTANCE ON CORN KERNEL SURFACES

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玉米籽粒表面抗损伤特性及分布研究

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ABSTRACT

This study addresses the issue of corn grain damage, which limits the efficiency of mechanized corn harvesting. The characteristics and distribution of corn grain surface damage resistance (CDDRS-SCK) were investigated. The "vulnerable" surface of the corn grain was selected for damage testing. The results revealed significant variations in damage resistance across different surfaces and locations of the corn grains. A regression model for damage resistance strength, based on surface position, was developed. Additionally, the impact of grain damage resistance on threshing damage was compared and analyzed for different threshing devices, in accordance with their working principles. This research provides theoretical insights and data support for the development of corn mechanized threshing technology and equipment.

摘要

针对玉米籽粒损伤制约玉米籽粒机械化收获的问题。本文开展了对玉米籽粒表面抗损伤强度(CDDRS-SCK)的特征及分布研究。选取"易伤"表面进行损伤试验，结果表明玉米籽粒不同表面、位置的抗损伤强度具有显著差异性，构建了基于表面位置的籽粒抗损伤强度回归模型。结合不同脱粒装置工作原理，对比分析了籽粒抗损伤特性对不同装置脱粒损伤的影响规律。为玉米机械化脱粒技术与装置开发提供了理论指导与数据支持。

INTRODUCTION

Threshing is a critical stage in the corn harvesting process. High-moisture corn kernels are particularly susceptible to damage during direct harvest due to the interaction and friction between the kernels and threshing teeth (*Kruszelnicka et al., 2024*). This damage not only affects the quality of the harvested corn but also compromises the secure storage of the grain *(Li et al., 2022*). Research has shown that the majority of physical damage to corn kernels occurs during threshing, primarily as a result of random collisions (*Petkevichius et al., 2008*). Consequently, minimizing threshing-induced damage has become a fundamental objective in the mechanical harvesting of corn.

Extensive research has been conducted on the characteristics of corn kernel damage, highlighting the influence of various factors on threshing outcomes. Corn variety and grain moisture content are significant determinants of the degree of threshing damage (*Sehgal et al., 1965*). Studies have shown that as the moisture content increases, the damage ratio of corn kernels also rises (*Yi et al., 2016*). Experimental findings further reveal that when corn kernels are positioned flat, moisture content exerts the greatest influence on the force required for kernel damage (*Yu et al., 2019*). To investigate the mechanisms of corn kernel damage, research has focused on the stresses experienced by kernels during damage. The internal structural properties of kernels are a primary cause of damage (*Dorsey-Redding et al., 1990*). Using electron microscopy, it was observed that fractures in maize subjected to high-temperature drying initially appeared in the silty endosperm and then rapidly propagated along the starch granule boundaries (*Gunasekaran et al., 1985*). Compression experiments on corn kernels have demonstrated that their damage-resistance strength varies significantly under different stress conditions (*Gao et al., 2011; Yuan et al., 1996*).

Zhao further established the maximum tensile stress that can be sustained by different kernel surfaces (*Zhao., 2012*). The effects of threshing structures and operational parameters on maize damage have also been extensively studied. Waelti identified drum speed, threshing gap, and rasp bar structure as the primary factors contributing to threshing damage (*Waelti, 1967*). Arnold demonstrated that reducing drum speed is the most effective method to decrease the rate of corn kernel damage (*Arnold et al., 1964*). Additionally, Wu showed that plate-tooth threshing offers advantages over traditional pin-tooth threshing, including a higher threshing rate, lower kernel breakage, and reduced power consumption (*Wu et al., 2006*). Geng explored the application of the flexible threshing concept and proposed a novel strategy to mitigate maize damage during the threshing process (*Geng et al., 2020*).

In conclusion, extensive research has characterized corn damage resulting from various mechanical components and forces, leading to the development of threshing devices with diverse mechanical structures and operating principles. However, the characteristics and spatial distribution of damage-resistance strength on the surface of corn kernels (CDDRS-SCK) have not been thoroughly investigated. This knowledge gap limits the understanding of the mechanisms underlying corn kernel damage and hinders the establishment of a robust foundation for parameter optimization in threshing device design. This study aims to analyze the CDDRS-SCK and its contributing factors, and to evaluate its potential influence on the structural and operational design of threshing machinery.

MATERIALS AND METHODS

Test equipment

The experimental data were obtained through a surface damage experiment conducted on corn kernels. The experimental setup consisted primarily of corn kernels, a custom-designed indenter, and a WDS-5 liquid crystal display electronic universal testing machine (accuracy: 0.2% F.S.), which included a lifting table, guide rails, a lift controller, a compression head, and a display screen. The corn kernels used in this study were from the widely cultivated "Zhengdan 958" variety, commonly grown in the Huanghuaihai region of China. The experimental apparatus for corn kernel surface damage is depicted in Fig. 1.

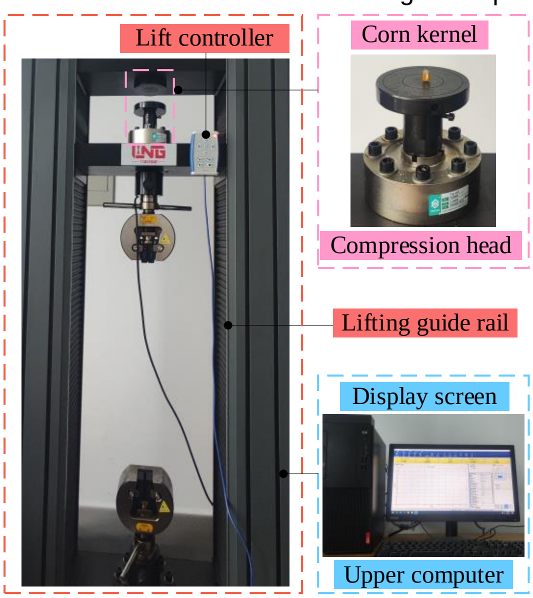


Fig. 1 - Corn kernel damage experiment device

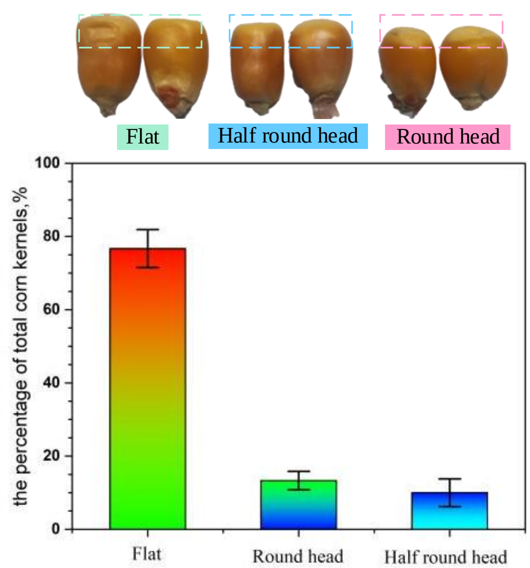


Fig. 2 - Corn kernel shape distribution map.

Selection of experimental corn kernels

Corn ears of the "Zhengdan 958" variety, with a moisture content of 24.5%, were harvested on September 26, 2024. Due to variations in component distribution and exposure to light, the head, middle, and tail sections of the corn ears exhibit distinct morphological characteristics. All corn kernels were manually peeled and categorized into three types based on their apex morphology: flat, round, and half-round. It was observed (Fig. 2) that approximately 80% of the kernels from the middle section of the corn ear are flat kernels.

Notably, flat kernels exhibit the lowest damage-resistance strength (DRS) among the three kernel types, as reported by (*Vyn et al., 1988*). This implies that as long as the flat kernels remain intact during threshing, other kernel types are unlikely to be damaged. Consequently, flat kernels are representative of the DRS of corn kernels and were selected as the focus for investigating the characteristics and distribution of damage-resistance strength on the surface of corn kernels (CDDRS-SCK) in this study.

Test scheme

Definition of corn kernel test surface

The internal heterogeneity of corn kernels, as illustrated in Fig. 3, contributes to variations in the damage-resistance strength (DRS) across different kernel surfaces. This necessitates a comprehensive investigation of the DRS across all kernel surfaces. Preliminary damage testing of corn kernels revealed that the DRS of the left and right sides of the kernel is nearly identical, while the DRS of the main surface is significantly lower than that of the back surface. To accurately determine the characteristics and distribution of damage-resistance strength on the surface of corn kernels (CDDRS-SCK), it is critical to focus on surfaces most susceptible to damage, as these are the first to fail under repeated impacts from threshing elements. Therefore, the main surface, top surface, and left surface of corn kernels—referred to as "damage-susceptible" surfaces—were selected for this study.

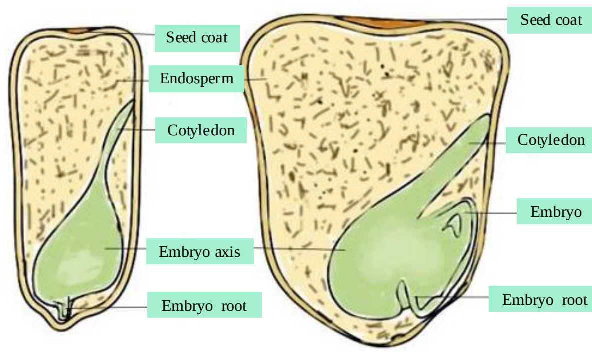


Fig. 3 - Corn kernel shape distribution map

Test procedure

A random sample of approximately 1000 hand-threshed corn kernels, with a moisture content of 24.3%, was selected for the study. To ensure uniform contact between the kernel surfaces and the indenter, the "damage-susceptible" surfaces of the experimental kernels were subjected to micro-grinding and marked using the point-marking method illustrated in Fig. 4. The marked points on each kernel surface were sequentially numbered from top to bottom and left to right. The indenter was carefully adjusted to align with a specific marked point on the corn kernel. Each marked point was then subjected to loading at a constant rate of 200 mm/min until the maximum damage-resistance force was recorded. To ensure reproducibility and statistical reliability, the average damage-resistance force F_i at each marked point was determined as the arithmetic mean of 20 repeated measurements, as expressed in equation (1):

$$F_i = \frac{1}{n}\sum_{j=1}^{n} F_{ij} \tag{1}$$

where F_i is the average force at point i; F_{ij} is the j-th force measured at the same point, and n=20.

a) Main surface b) Side surface c) Top surface

Fig. 4 - Different surface markers of corn kernels

Test evaluation index and calculation method

(1) Maximum damage-resistance force (F)

The maximum damage-resistance force (F) is defined as the highest force that can be applied to the surface of corn kernels before visible damage occurs. It corresponds to the maximum load sustained by the kernels under continuous application of pressure using a testing machine.

(2) Damage-resistance strength (DRS)

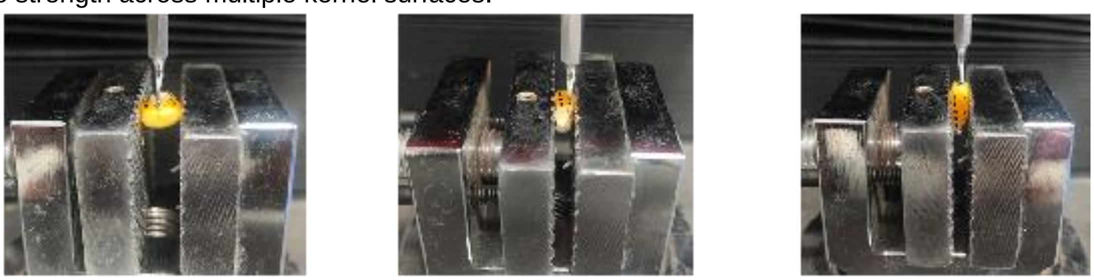
Damage-resistance strength (DRS) is defined as the maximum contact stress that corn kernels can endure without sustaining damage, serving as a critical parameter for evaluating their load-bearing capacity. To enhance the precision of DRS measurements across the surface of corn kernels, the concept of equivalent damage-resistance strength ($EDRS$) is introduced. The $EDRS$ is calculated as the mean DRS value derived from n experiments conducted at the same location on different corn kernels. The following formula is used to determine the $EDRS$:

$$\sigma_0 = \sigma_{\mathrm{v}} = \frac{1}{n}\sum_{i=1}^{n}\frac{F_i}{A_0} \tag{2}$$

where, σ_0 represents the DRS at a specific location on the corn kernel, σ_{v} denotes the $EDRS$ at the same location, F_i is the maximum damage-resistance force recorded at the specific position across n repeated experiments on different kernels, A_0 is the contact area between the kernel and the custom-made indenter during the experiment, approximately 1 mm².

Test

The aforementioned testing protocol was applied to conduct loading tests at different locations on the same corn kernel until visible damage occurred. As illustrated in Fig. 5, the following tests were performed. For the main surface (a) of the corn kernel, two loading tests were conducted sequentially from left to right. For the side surface (b), a total of 14 loading tests were performed from left to right. For the side surface (c), nine loading tests were conducted, also from left to right. This systematic approach ensured comprehensive evaluation of the damage-resistance strength across multiple kernel surfaces.



a). Main surface b). Side surface c). Top surface

Fig. 5 - Surface loading test of different corn kernels

Based on the test sequence described above, a series of repeated experiments were conducted, as shown in Fig. 6. The resulting trends in the load-displacement curves were generally consistent. The average load-bearing capacity across different surfaces of the corn kernels exhibited a similar pattern: as the indenter displacement increased, the load on the kernel surface increased linearly until surface damage occurred, at which point the load-bearing capacity dropped abruptly. This behavior can be attributed to the elastic deformation of the kernels during the initial loading phase. Within this elastic deformation range, the stress on the kernel surface increases linearly with the indenter displacement. However, when the load exerted by the indenter exceeds the kernel surface's load-bearing capacity, the kernel surface fails, leading to a sudden decline in its carrying capacity. These findings highlight the importance of controlling the applied load during the mechanized harvesting of corn. Ensuring that the load remains below the kernel surface's carrying capacity is critical for maintaining harvest quality and minimizing kernel damage.

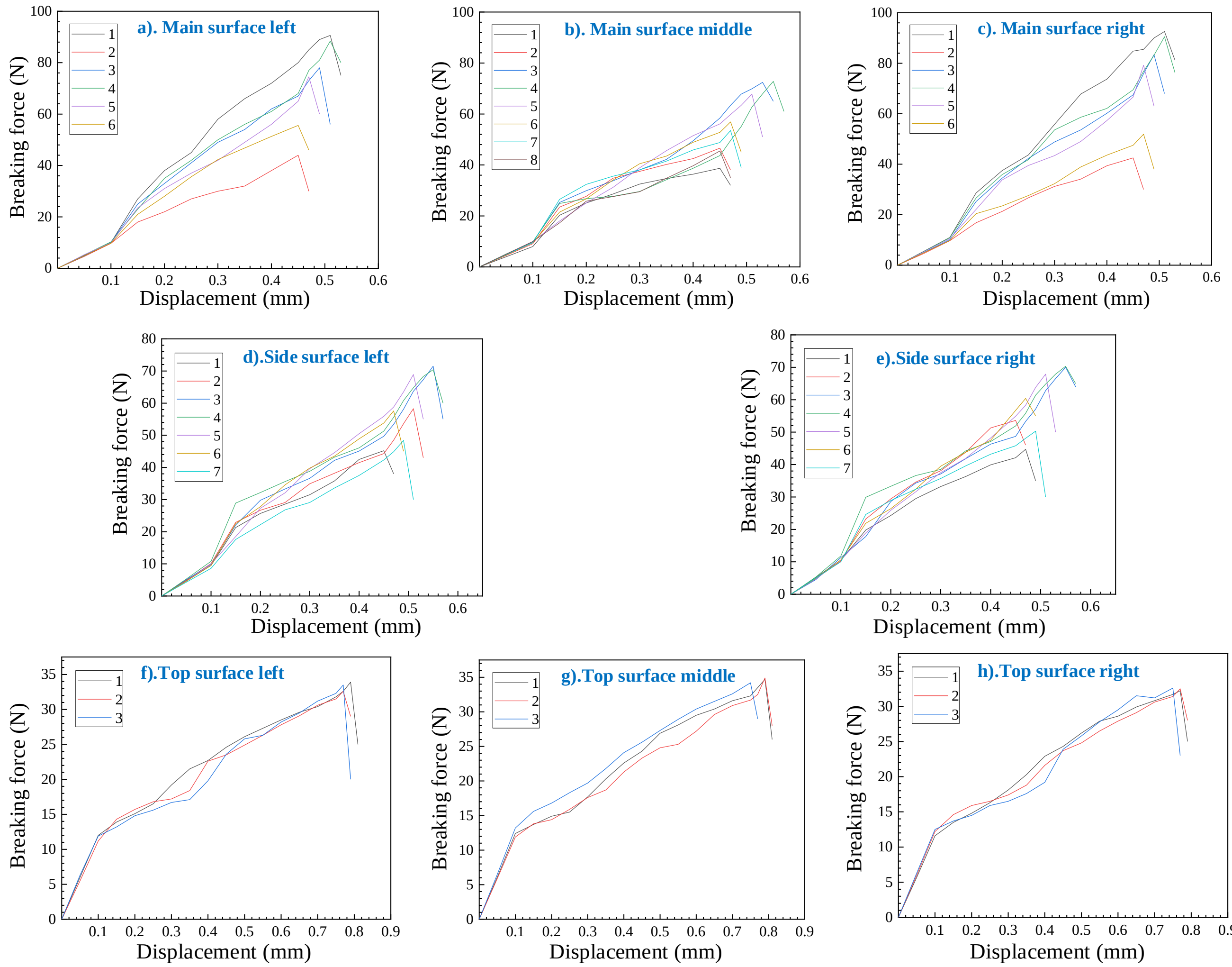


Fig. 6 - Grain surface stress curve

RESULTS AND DISCUSSIONS

Results

The results of the corn kernel damage experiment are summarized in Table 1, highlighting the maximum damage-resistance force for each surface. The data indicate that the main surface of the corn kernel exhibits the highest maximum damage-resistance force, while the top surface demonstrates the lowest. These findings suggest that during corn harvesting, kernel damage can be effectively minimized if the force applied by the threshing element remains below the maximum damage-resistance force of the top surface. This observation aligns with the conclusion that beak threshing results in reduced threshing damage, as reported by (*Li et al., 2015*).

Table 1

The damage test results of corn kernel (moisture content 24.3 %)

Surface		The damage-resistance force of marked points on corn grain (N)							
		1[*]	2[*]	3[*]	4[*]	5[*]	6[*]	7[*]	8[*]
Main	left	44.5±9.05 [†]	77.2±5.21	90.6±3.76	88.4±3.58	74.6±4.65	54.1±8.57	-	-
	middle	38.7±9.72	46.6±8.74	72.4±5.45	72.8±5.28	67.8±4.26	56.9±4.04	53.5±3.25	45.5±2.57
	right	42.5±7.22	79.2±4.64	92.5±2.83	90.5±3.05	83.4±4.25	51.9±5.12	-	-
Side	left	45.2±4.67	58.3±2.80	71.5±2.47	70.4±1.97	68.9±3.44	57.6±4.35	48.4±3.77	-
	right	44.7±4.36	53.6±3.29	70.3±3.15	70.0±2.37	67.9±3.20	60.4±4.17	50.3±4.56	-

Surface		The damage-resistance force of marked points on corn grain (N)							
		1[*]	2[*]	3[*]	4[*]	5[*]	6[*]	7[*]	8[*]
Top	left	33.9±1.88	32.6±2.17	33.5±1.57	-	-	-	-	-
	middle	34.7±1.76	34.9±1.85	34.2±2.46	-	-	-	-	-
	right	32.2±2.42	32.5±1.71	32.6±1.83	-	-	-	-	-

[*] The numbering of marked points follows the instructions in Fig 4. 44.5±9.0; [†] represents the damage resistance force of the first marked point on the left side of the main surface of the corn kernel is 44.5 N and the mean square is 9.05.

While the damage-resistance force provides a partial measure of the relationship between applied force and corn kernel damage, failure theory indicates that a large applied force does not necessarily cause damage. Damage to the corn kernel surface or interior tissue occurs only when the externally applied load exceeds the material's inherent resistance strength. To better quantify this phenomenon, the equivalent damage-resistance strength (EDRS) at each marked point was calculated in this study. To visually represent the characteristics and distribution of damage-resistance strength on the surface of corn kernels (CDDRS-SCK), all calculated results were processed using the Origin software. The resulting contour maps of damage-resistance strength distribution across the three kernel surfaces are shown in Fig. 7. The analysis revealed distinct differences in the characteristics and distribution of damage-resistance strength across the three surfaces, as well as variations within each individual surface. These findings highlight the need for further investigation into the distribution and characteristics of damage-resistance strength on each kernel surface, with a focus on identifying the locations with the highest resistance to damage.

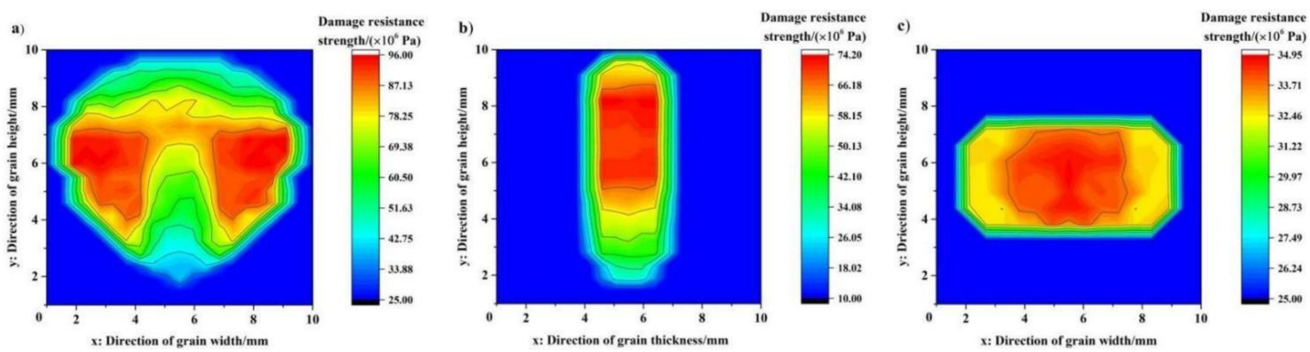


Fig. 7 - The distribution of damage-resistance on the a) main, b) side, and c) top surface of the corn kernel

Characteristics and distribution of damage resistance strength on the main surface of corn kernels

The characteristics and distribution of damage-resistance strength on the main surface of the corn kernel (CDDRS-MSCK) are shown in Fig. 8(a). The x-axis is defined along the lower boundary of the corn kernel, while the y-axis is defined along its left boundary. The CDDRS-MSCK is analyzed in both the width and height directions of the corn kernel. The distribution curve of damage-resistance strength in the horizontal direction at y=6 mm, which is symmetrically distributed along the width, is depicted at the top of Fig. 8(a). This curve represents the distribution and characteristics of damage-resistance strength along the width of the kernel's main surface. The results indicate that the damage-resistance strength in the middle of the kernel is approximately 74.5×10^6 Pa, while it symmetrically increases to about 97×10^6 Pa on both sides of the kernel. This pattern is attributed to the structural composition of the kernel in the width direction: the sides predominantly consist of endosperm deposits, whereas the central region mainly contains cotyledons, the germ, and the radicle, which are structurally weaker. Based on the CDDRS-MSCK findings, it is recommended that when the main surface is selected as the primary stress surface for threshing, the loading position should target the sides of the kernel while avoiding the central region. Additionally, to prevent the threshing load from concentrating on the kernel's center, the contact position between the threshing element and the kernel should span more than half the kernel's width.

The vertical directions x = 3.5mm, 5.5mm, and 7.5mm are chosen to evaluate the damage-resistance strength in the height direction at the right of Fig 6. The characteristics and distribution of damage-resistance strength at x = 3.5mm and x = 7.5mm are essentially identical in that the damage-resistance strength of the height direction range y∈[4.2mm, 6.85mm] approaches 90×10^6 Pa. While the damage-resistance strength decreases gradually in height direction between y∈[0mm, 4.2mm] and y∈[6.85mm, 10mm]. This is because the region is predominantly endosperm and has a progressive maturation pattern. At a height of x = 5.5mm, the damage-resistance strength of the higher component is greater than that of the smaller lower portion. That's because, in the direction of height x = 5.5mm, the structures at the bottom are the radicle, germ, and hypocotyl, while the structures at the top are the endosperm structure. And during corn development, water is transferred from the radicle to the endosperm, and the kernel's aggregation leads the upper surface to lose more water than the lower section.

The vertical positions x=3.5 mm, , 5.5 mm, and 7.5 mm were selected to evaluate the damage-resistance strength in the height direction. The characteristics and distribution of damage-resistance strength at x=3.5 mm and x=7.5 mm are largely similar. In the height range y∈[4.2 mm,6.85 mm], the damage-resistance strength approaches approximately 90×10^6 Pa. However, the damage-resistance strength decreases progressively in the height ranges y∈[0 mm,4.2 mm] and y∈[6.85 mm,10 mm]. This reduction is attributed to the predominance of endosperm tissue in these regions, which exhibits a gradual maturation pattern. At x=5.5 mm, the damage-resistance strength in the upper region is higher than in the lower region. This difference arises from the structural composition along this height direction: the lower portion predominantly contains the radicle, germ, and hypocotyl, whereas the upper portion consists mainly of endosperm tissue. During corn development, water transfer occurs from the radicle to the endosperm, leading to differential moisture loss. The upper region, composed primarily of endosperm, loses more water due to aggregation effects, resulting in greater resistance compared to the lower section.

When the main surface of the corn kernel is subjected to loading by the threshing element, it is recommended to select loading positions within the width range x∈[2 mm,4.5 mm]∪[6.5 mm,9 mm] and the height range y∈[4.2 mm,6.85 mm]. This selection is expected to be more effective in reducing the corn kernel damage rate.

Characteristics and distribution of damage resistance on the side surface of corn kernels

As illustrated in Fig. 8(b), the characteristics and distribution of damage-resistance strength on the side surface of the corn kernel (CDDRS-SSCK) are presented. In the thickness direction, the damage-resistance strength exhibits a trapezoidal distribution. This pattern arises because the sides of the corn kernel predominantly consist of endosperm, which has a relatively homogeneous texture. Within a specific range, the damage-resistance strength remains largely uniform. However, as the edge of the kernel is approached, the resistance to damage decreases sharply due to stress concentration at the borders. Consequently, when the side of the kernel is subjected to loading by a threshing element, the loading position along the thickness direction has minimal impact on kernel damage. The damage-resistance strength along the vertical direction at x=5.5 mm follows an upward-sloping "bathtub" distribution. The maximum damage-resistance strength is observed in the height range y∈[5.75 mm,8.1 mm], while it decreases both above and below this range. The decline is more pronounced in the downward direction, as the middle and upper portions of the kernel are primarily composed of endosperm, with greater endosperm accumulation in the middle. In contrast, the lower portion consists mainly of radicle tissue, which exhibits lower resistance to damage.

Based on the analysis, selecting a threshing loading position within the height range y∈[5.75 mm,8.1 mm] along the side surface of the corn kernel is more effective in reducing the kernel damage rate during threshing.

Characteristics and distribution of damage resistance on the top surface of corn kernels

The characteristics and distribution of damage-resistance strength on the top surface of the corn kernel (CDDRS-TSCK) are analyzed along the width and thickness directions, as shown in Fig. 8(c). The damage-resistance distribution curve along the width direction at y=5.5 mm is illustrated in the upper curve of Fig. 8(c), which exhibits an "inverted bathtub" shape. This pattern arises because the top surface of the corn kernel primarily consists of endosperm, resulting in generally comparable damage-resistance strength. However, the longer endosperm precipitation time in the central region produces a smaller peak in the middle of the curve.

The curve further demonstrates that the damage-resistance strength on the top surface remains stable within the width range x∈[2.1 mm,8.9 mm] before rapidly decreasing. This decline is primarily attributed to the narrow upper and lower kernel structures and the stress concentration at the edges. In the thickness direction, the characteristics and distribution of damage-resistance strength, depicted on the right side of Fig. 10, resemble those observed in the thickness direction of the corn kernel's side surface. This similarity indicates that variations in loading positions along the thickness direction have minimal impact on threshing damage.

Therefore, to minimize the risk of corn kernel damage, the threshing element should target the width range x∈[2.1 mm,8.9 mm] on the top surface of the kernel.

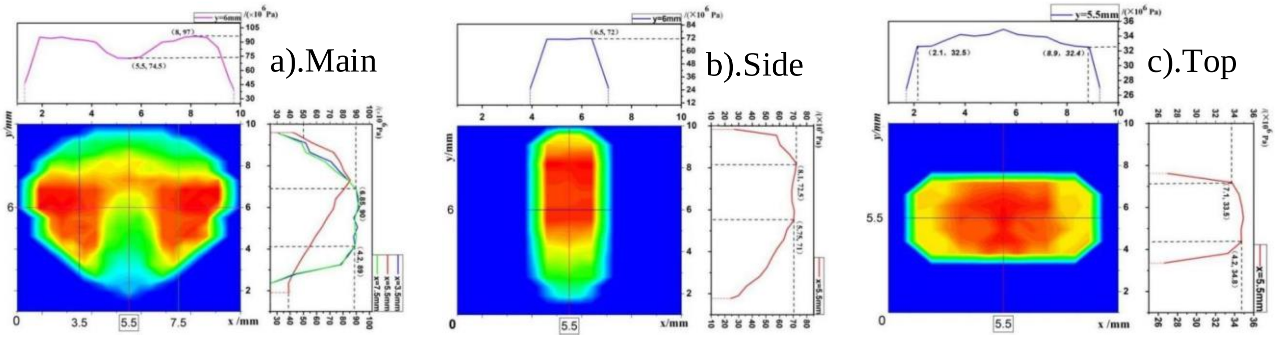


Fig. 8 - Distribution of Damage Resistance on the Surface of Corn Kernels

Discussions

Development of a damage resistance model for corn Kernels

Based on the test results and the distribution patterns of damage-resistance strength on the main, side, and top surfaces of the corn kernel, a spatial rectangular coordinate system was established. The origin was defined at the seed radicle. The Z-axis extends forward perpendicular to the top surface above the origin, the X-axis points leftward perpendicular to the side surface, and the Y-axis points outward perpendicular to the main surface. This coordinate system adheres to the right-hand rule. Using Design Expert software, response surface analysis was performed to construct a damage-resistance model for the typical surfaces of the corn kernel, as illustrated in Fig. 11. The nonlinear regression equation representing the damage-resistance strength of the corn kernel surface was established as follows:

$$\begin{cases} \sigma_z = -29.56x^2y^2 - 36y^3 - 0.85xy^2 + 22.39x^2y - 32.49y^2 + 13.4x^2 - 0.1xy + 39.77y + 0.27x + 74.6 & (z = \pm 2mm) \\ \sigma_x = 24.06y^2 - 0.12zy + 13.69y + 0.11z + 68.41 & (x = \pm 4mm) \\ \sigma_y = -0.42z^2 - 1.52x^2 + 0.098xz + 0.026z + 34.54 & (y = \pm 5mm) \end{cases} \quad (3)$$

In the established model, x denotes the width of the corn grain. y represents the height of the corn grain. z corresponds to the thickness of the corn grain. σ_z is the nonlinear regression equation representing the damage resistance strength of the principal plane of the maize kernel. σ_x is the nonlinear regression equation for the damage resistance strength of the side surface of the corn kernel. σ_y is the nonlinear regression equation for the damage resistance strength of the top surface of the corn kernel.

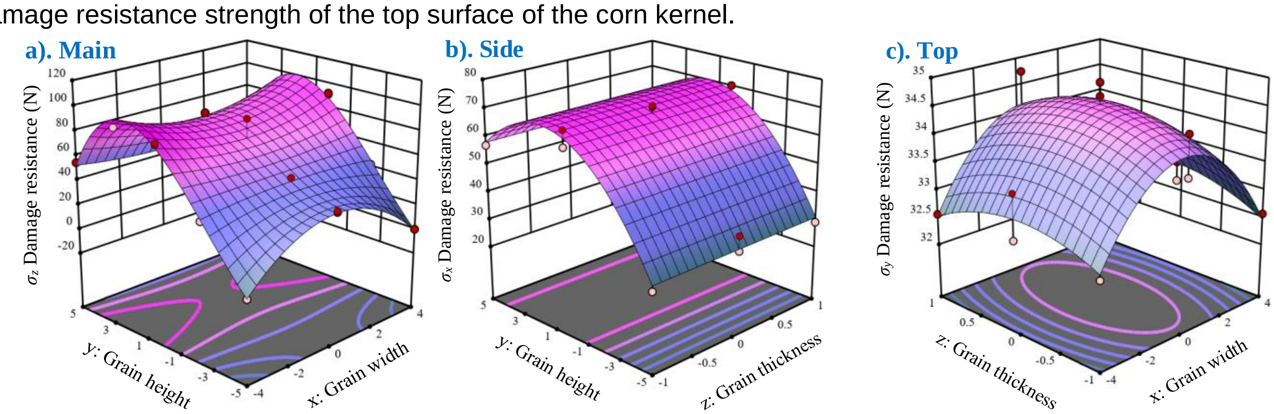


Fig. 11 - The damage resistance strength model of maize kernel typical surface

Among the models, the determination coefficients for the main plane and side surface damage strength were R^2=0.9726 and R^2=0.9764, respectively, with significance levels of the lack-of-fit terms P>0.25, indicating a strong fitting performance for these models. In contrast, the determination coefficient for the top surface damage strength model was R^2=0.8170, with a lack-of-fit significance level of P>0.25. This comparatively lower fitting accuracy is attributed to the stable distribution of damage strength on the top surface, which is less influenced by location variability. The models enable more accurate prediction of the damage strength of corn kernels across different surfaces and locations, providing valuable guidance for selecting optimal threshing loading positions and reducing threshing damage.

Effect of kernel damage resistance on mechanical threshing performance

Our findings reveal the characteristics and distribution of damage-resistance strength on the defined "damage-susceptible" surfaces of corn kernels. The distribution of damage-resistance strength varies across different kernel surfaces due to the influence of internal structural differences, yet follows specific patterns in certain directions. These distribution laws provide a basis for describing, analyzing, and optimizing the design, working principles, and application of corn harvesting equipment. Building on the analysis of the characteristics and distribution of damage-resistance strength on the surface of corn kernels (CDDRS-SCK), this section explores the influence of various threshing devices and threshing gaps on threshing-induced damage.

Corn kernel threshing primarily employs two methods: tangential flow and axial flow. The tangential flow threshing cylinder operates at rotation speeds ranging from 800 r/min to 1200 r/min (*Fu et al., 2018*), resulting in significant forces applied to the corn kernel surface. Previous analysis indicates that the surface of a corn kernel cannot withstand forces exceeding its maximum damage-resistance force. Under comparable conditions, the load exerted by tangential flow threshing is greater than that of axial flow threshing, leading to a higher rate of kernel damage. This observation aligns with practical experience and explains why most corn harvesters utilize the axial flow threshing technique. Axial flow threshing devices can be further categorized into two modes: transverse axial flow threshing and longitudinal axial flow threshing (*Tang et al., 2022; Wang, 2019*).

These methods differ significantly in the feeding mechanism and action process of the corn ears. In transverse axial flow threshing, the ears are fed radially and move along the axial direction of the drum, with the threshing element completing the process. During this procedure, the initial loading position of the corn kernels is on the top surface, which later transitions to the side surface as the direction of ear movement changes from radial to axial. According to the analysis in Table 1 and the section "The Characteristics and Distribution of Damage-Resistance Strength on the Top Surface of the Corn Kernel," the damage-resistance strength (DRS) of the top surface is the lowest, ranging between 33×10^6 Pa and 35×10^6 Pa. Consequently, this threshing method tends to cause more damage to kernels. In contrast, longitudinal axial flow threshing exerts force consistently on the side surface of the kernel, as the corn ears move entirely in the axial direction. The results from the section "The Characteristics and Distribution of Damage-Resistance Strength on the Side Surface of the Corn Kernel" reveal that the DRS of the side surface is significantly higher, ranging between 60×10^6 Pa and 70×10^6 Pa. This superior strength reduces the likelihood of kernel damage compared to transverse axial flow threshing. These findings align with practical threshing results, where longitudinal axial flow threshing is associated with a lower damage rate (*Wang et al., 2021*).

The influence of the threshing gap on mechanical threshing loss is analyzed theoretically based on the characteristics and distribution of damage-resistance strength on the surface of corn kernels (CDDRS-SCK). Proper regulation of the threshing gap is critical to minimizing threshing loss, as excessively small or large gaps can lead to undesirable outcomes (*Yang et al., 2021*). When the threshing gap is too small, the increased threshing load results in the threshing element acting on the top surface of the corn kernel, which has the lowest damage-resistance strength, or on the lower portions of the side and main surfaces, where the damage-resistance strength decreases gradually from approximately 55×106 Pa to 35×106 Pa. This inevitably exacerbates kernel damage. Conversely, when the threshing gap is too large, the threshing element primarily interacts with the top surface of the kernel, which also increases threshing loss. Therefore, an appropriate threshing gap is essential to reducing kernel damage, underscoring the need for adjustable threshing gaps in corn harvesters. According to previous studies, the threshing load is highest when processing the entire corn ear, and it decreases significantly as kernels are removed (*Li et al., 2017*).

Regardless of whether a tangential or axial flow threshing mechanism is used, a higher rotational speed of the threshing drum is required at the start of threshing to ensure the removal of kernels from the entire ear. During this initial phase, threshing damage is inevitable due to the mutually exclusive nature of effective threshing and damage prevention. However, as the structure of the threshing mechanism causes the corn ear to align parallel to the drum after partial threshing, the side surface of the corn kernel is subjected to greater stress. The findings in the section "The Characteristics and Distribution of Damage-Resistance Strength on the Side Surface of the Corn Kernel" indicate that the damage-resistance strength along the height direction of the side surface follows an upward-sloping "bathtub" distribution, whereas the strength along the thickness direction remains relatively uniform. Based on these results, it is recommended that the threshing gap be adjusted such that the threshing load is primarily exerted on the upper side of the corn kernel. For the "Zhengdan 958" corn variety studied here, it is advised that the action point of the threshing element be positioned approximately 2–4 mm from the kernel's top surface. While the proposed threshing position is specific to the "Zhengdan 958" variety, it is theoretically derived from experimental results and can serve as a valuable reference for analyzing and selecting optimal threshing positions for other corn varieties. Due to the variability among corn varieties, further adjustments may be necessary to adapt these recommendations to other cultivars.

CONCLUSIONS

This study addresses the issue of corn grain damage during the harvest of high-moisture corn using a combine harvester. A method for evaluating the surface damage load of corn grains is proposed. Multiple sets of loading tests were conducted, with the main, side, and top surfaces of the corn grains subjected to different loading conditions. The aim was to investigate the damage resistance of the various surfaces of the corn grains.

(1) Several groups of surface damage loading tests were conducted on different types of corn grains to investigate the distribution of damage resistance across the flat grain surface. The results revealed significant variations in the damage resistance of the "vulnerable" surface of the flat grain. Specifically, the surface exhibited the highest resistance, followed by the side surface, with the top surface showing the lowest resistance.

(2) By measuring the characteristics and distribution of damage resistance across different surfaces of corn grains, the variation in damage resistance on typical surfaces was determined. Based on the differences in the internal structure of corn grains, a distribution model of damage resistance for the typical surfaces was developed. The main factors influencing the variation in damage resistance were identified. This research provides a basis for selecting optimal threshing loads and positions in the mechanized threshing process of maize.

(3) Based on the characteristics and distribution of the surface damage resistance (CDDRS-SCK) of corn grains, the factors contributing to the lower damage rate observed in longitudinal axial flow threshing were analyzed. Theoretical analysis of the influence of the threshing gap on mechanical threshing was also conducted, and an optimal loading position for corn threshing was proposed. This study provides data support for the development of corn threshing technology and equipment, as well as for determining key operational parameters.

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