

Original papers

Coupling modelling and validation of multi-modal intrinsic parameters of maize kernel based on discrete element method

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ABSTRACT

This study aims to address the issue of breakage during sowing, threshing, and storage of maize kernels, which reduces the quality of mechanical operations. Using uniaxial compression tests, the peak load of maize kernels was determined under different moisture content, axial ratio, and pressure direction conditions. A constitutive model was developed to describe the moisture content, axial ratio, peak load, and displacement of maize kernels under abdominal pressure. Based on the principle of hexagonal closest packing, a particle model was constructed to precisely represent the outer contour and internal dense structure of maize kernels. The bonding parameters of the Bonding V2 model were calibrated through orthogonal experiments, and the theoretical load peak relative to the actual error was 1.7%. Explored how the required calibration parameters should change under the condition of 0.2–0.5 mm particle radius, the parameters corresponding to the particle with the current radius r_0 are p , n , and s . Once the particle radius reaches r_0/m , the corresponding parameters should be updated to $m2p$, $m2n$, and s . Through response surface analysis, a regression equation was developed that quantitatively relates moisture content, axial ratio, and bonding parameters to the maximum load and displacement of the bridge. The model's relative error was 4.5%. By combining DEM-MBD simulation with bench testing, the model's mechanical characterisation performance was verified. When the seeder's forward speed is 8 km/h, the simulation results indicate that wear is most severe within the range from finger clamp closure to seed rotation of 40°. At this stage, the average resultant force on the kernels was 1.03N, and the bond fracture ratio was 2.49%. It can better characterize the sowing damage process. Research can provide a model to support reducing mechanical losses during maize sowing and threshing.

1. Introduction

Maize is an important global food crop and industrial raw material. It is susceptible to complex mechanical loads, such as compression, impact, and shearing, during harvesting, transportation, processing, and sowing, leading to quality degradation and economic losses (Liu et al., 2019; Qiao et al., 2022; Ziegler et al., 2021). In the mechanized harvesting process of high-moisture maize, the grain breakage rate has exceeded 5% (Dong et al., 2024). However, in maize exported from developed countries, the proportion of intact grains is only 83.7% (Chen et al., 2023). Research has shown that factors such as moisture content and axial ratio of maize kernels significantly affect their mechanical

properties (Buggenhout et al., 2013; Guo et al., 2022; Kruszelnicka et al., 2024). Currently, there is no clear correlation between grain mechanical properties and damage behavior under complex loading, and no established modelling method accurately characterizes this relationship. Therefore, developing a model that accurately describes the mechanical properties and damage behavior of maize kernels is crucial for achieving low-damage mechanized operations for maize harvesting and sowing.

Since its initial use in agricultural engineering (Crini, 2006), the Discrete Element Method (DEM) has experienced significant development. Early research successfully adapted this method to model the complex shapes and interactions of various crops, such as maize and olives (Gonzalez-Montellano et al., 2012). More recently, studies have focused on improving parameter calibration techniques, leading to

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Nomenclature

DEM	Discrete Element Method
MBD	Multi-Body Dynamics
HCP	Hexagonal Closest Packing
p	Normal/Shear Stiffness per unit area
n	Normal/Shear Strength
s	Bond Disk Scale

ongoing progress in characterizing the physical and mechanical properties of agricultural materials (Horabik & Molenda, 2016). The Particle Bonding Model (PBM) simulates the overall mechanical behavior of materials by adding bonding forces between individual particles, and is commonly used to model the fracture behavior of brittle materials like rocks. It has also been extended to study the mechanical properties of agricultural materials (Leblicq et al., 2016; Li et al., 2002 Mousaviraad & Tekeste, 2024; Petingco et al., 2020).

In the study of discrete element modelling of maize kernels, the multi sphere assembly method has been used to construct their geometric models (Chen et al., 2020; Wang et al., 2020; Wang et al., 2017), and other studies have used polyhedra to simulate the external contour of the kernels (Chiaravalle et al., 2023; Chiaravalle et al., 2025). For other crops, the potato model can be represented by multiple spheres (Yue et al., 2025). In contrast, the spindle-shaped appearance of rice seeds can be geometrically reconstructed by concatenating polyhedra or multiple spheres (Yang et al., 2025; Zhang et al., 2025). The modelling of wheat grains is also completed using the multi-sphere splicing method (Petingco et al., 2022). In terms of the interaction between materials and machinery, previous studies have established a multi-scale constitutive model by integrating Burgers creep model and Hertz Mindlin contact theory (Li et al., 2022); By combining the discrete element method and the bonded particle model, the influence of three centrifugal disk structural parameters on the crushing characteristics of maize was systematically analyzed (Su et al., 2022); Based on the discrete element

method, the correlation between material properties, processing parameters, and quality properties of maize stover during blade milling was explored (Xia et al., 2023). A discrete element model of the maize threshing process was constructed (Ji et al., 2024). However, traditional discrete element methods have limitations in accurately reflecting the mechanical properties of typical crops, such as maize kernels. Firstly, the geometric representation is inaccurate, and the multi-sphere splicing or simple polyhedral models used are too complex to accurately represent the grain shape. Conventional particle-filling methods are prone to issues such as significant particle gaps, disorderly arrangement, and loose structure, which, in turn, lead to inaccurate characterisation of mechanical performance and errors in subsequent calibration of bonding parameters for the Bonding V2 model. Secondly, there is a lack of effective correlation between intrinsic parameters, such as grain moisture content and axial ratio, and bonding parameters, and no established mechanism linking intrinsic bonding parameters to mechanical properties.

Therefore, innovation is needed in modelling methods and parameter calibration systems. This study proposes a novel modelling method that combines geometric boundary recognition and the construction of the densest hexagonal stacking structure, addressing the limitations of existing research, which often employs multi-sphere concatenation or simple polyhedron modelling. This method can accurately reconstruct the grain's geometric shape and simulate its dense internal structure, thereby characterizing its fundamental mechanical properties more accurately. In response to the lack of effective correlation between intrinsic and bonding parameters, this study adopted a discrete-element bonding model to systematically analyze the compression fracture characteristics of maize kernels under different moisture content, axial ratio, and pressure direction. It established a functional relationship between moisture content and the axial-ratio force-displacement curve.

Additionally, a regression equation for the maximum load and displacement of maize during compression was derived by combining simulation and orthogonal experiments. Based on this, the relationship between intrinsic parameters and bonding parameters was quantitatively established using the maximum load and its displacement as the bridge. Validate the model through single-factor experiments and

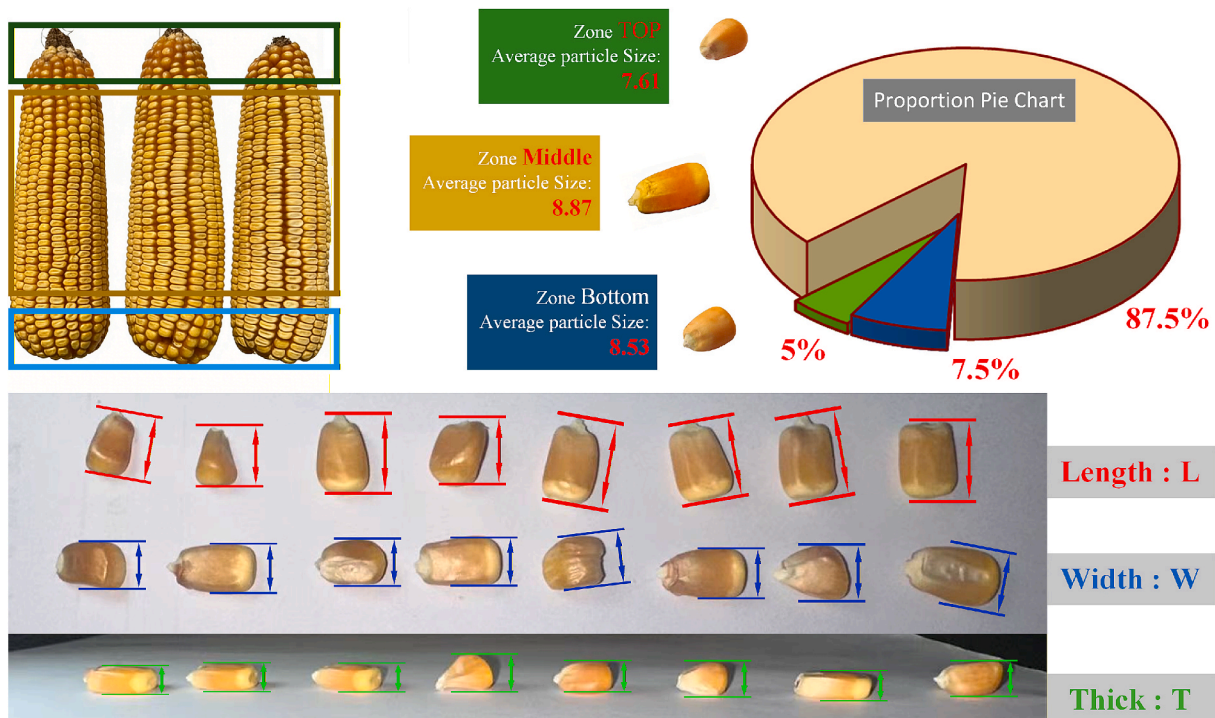


Fig. 1. Distribution and explanatory diagram of maize kernels

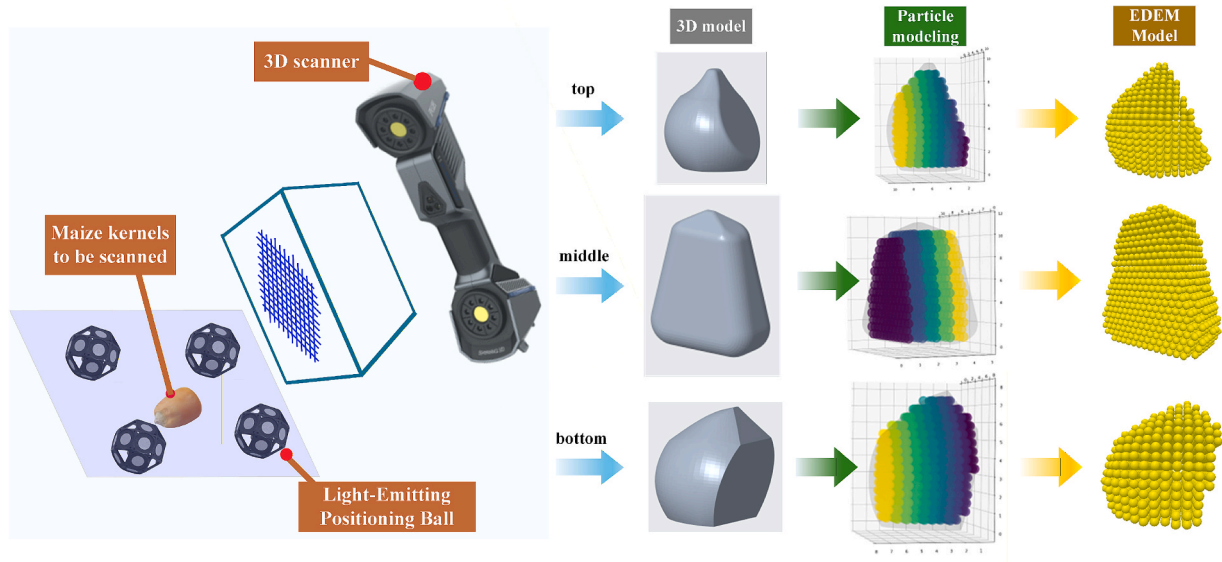


Fig. 2. Acquisition of STL file of maize kernel shape and filling of internal particles

simulations. By combining on-site planting with a mechanical seed-metering device and DEM-MBD coupling simulation, the correlation between finger clamping force and grain damage was explored, providing new theoretical references for fine modelling and efficient simulation of crops such as maize.

2. Materials and methods

This research examined the impact of moisture content, location, axial ratio, and loading direction on the mechanical properties of maize kernels using uniaxial compression tests. An accurate maize kernel model was constructed based on the principle of the Hexagonal Closest Packing, and further validated using the DEM-MBD coupled simulation method.

2.1. Test materials of maize kernels

The maize used in the experiment was sourced from Jilin Province. Use maize kernels that have been threshed to remove impurities, have a complete appearance, and have no internal damage as experimental materials. To investigate the mechanical properties of maize kernels at different moisture levels, four sample groups with target moisture contents of 9.1%, 16.4%, 20.8%, and 25.7% (wet basis) were prepared by soaking. The process was as follows: Maize kernels were first dried in an oven to reach a constant weight. They were then soaked for 1 hour, and a batch of samples was taken every 2 hours, resulting in four batches. After removal, surface moisture was wiped off, and the kernels were weighed to determine the actual moisture content. Finally, any batches showing significant deviations from the target moisture levels were excluded from the analysis.

The morphology of grains in different parts of the same maize ear varies greatly. To clarify the mechanical properties of grains from different parts, this study divided maize into top, middle, and bottom segments, as shown in Fig. 1. According to statistics, the number of grains accounted for 5%, 87.5%, and 7.5% of the total, respectively.

For kernels in the same part, there are also differences in geometric shapes, which can be quantified by calculating the axial ratio.

$$R = \frac{S}{F} \quad (2.1)$$

$$D = \left(L \times \frac{(W+T)^2}{4} \right)^{\frac{1}{3}} \quad (2.2)$$

In formula (2.1) and (2.2), $S = W / L$; $F = T / W$

R is the axial ratio; S is the slender length, %; F is the flatness, %; L is the length, mm; W is the width, mm; T is the thickness, mm; D is the particle size, mm.

Measure the particle size distribution (length, width, thickness) of the kernels using a vernier caliper, with 100 kernels per group. The average particle size of the three groups of kernels is 7.61 ± 0.46 mm for the top segment, 8.87 ± 0.22 mm for the middle segment, and 8.53 ± 0.45 mm for the bottom segment.

2.2. Obtaining and modelling the precise shape of maize kernels

Based on the study of the geometric dimensions of maize kernels, as shown in Fig. 2, this paper uses a 3D scanner, the Tianyuan FreeScan UE7 model, with a maximum measurement accuracy of 0.02 mm, to capture the geometric shapes of the top, middle, and bottom segments of the kernels, and outputs standard STL format files to accurately create different types of maize kernel models.

To address the common issues of irregular particle arrangement and uneven gaps in STL geometric filling in traditional simulation software, this paper introduces a new arrangement method that combines geometric boundary recognition with the construction of the Hexagonal Closest Packing (HCP). The process is shown in Fig. 3, and particle filling models of different parts of maize kernels, along with their corresponding 3D coordinates, are successfully generated. In an ideal HCP lattice, each sphere contacts 12 neighboring spheres. However, to account for the non-zero shell thickness assigned to particles in EDEM 2022, the centre-to-centre distance between adjacent spheres was slightly increased to 1.02 times the particle diameter. During the filling process, the algorithm calculates theoretical particle positions based on the specified radius and the exact geometric constants of the HCP structure in both horizontal and vertical directions. This guarantees that the packing is strictly non-penetrating, with no particle overlap. For the same maize kernel STL shell model, the HCP modelling method results in an average increase of 7.6% in particle filling quantity compared to traditional filling algorithms, thereby enhancing the model's filling density and structural density.

Subsequently, the obtained coordinates were imported into EDEM

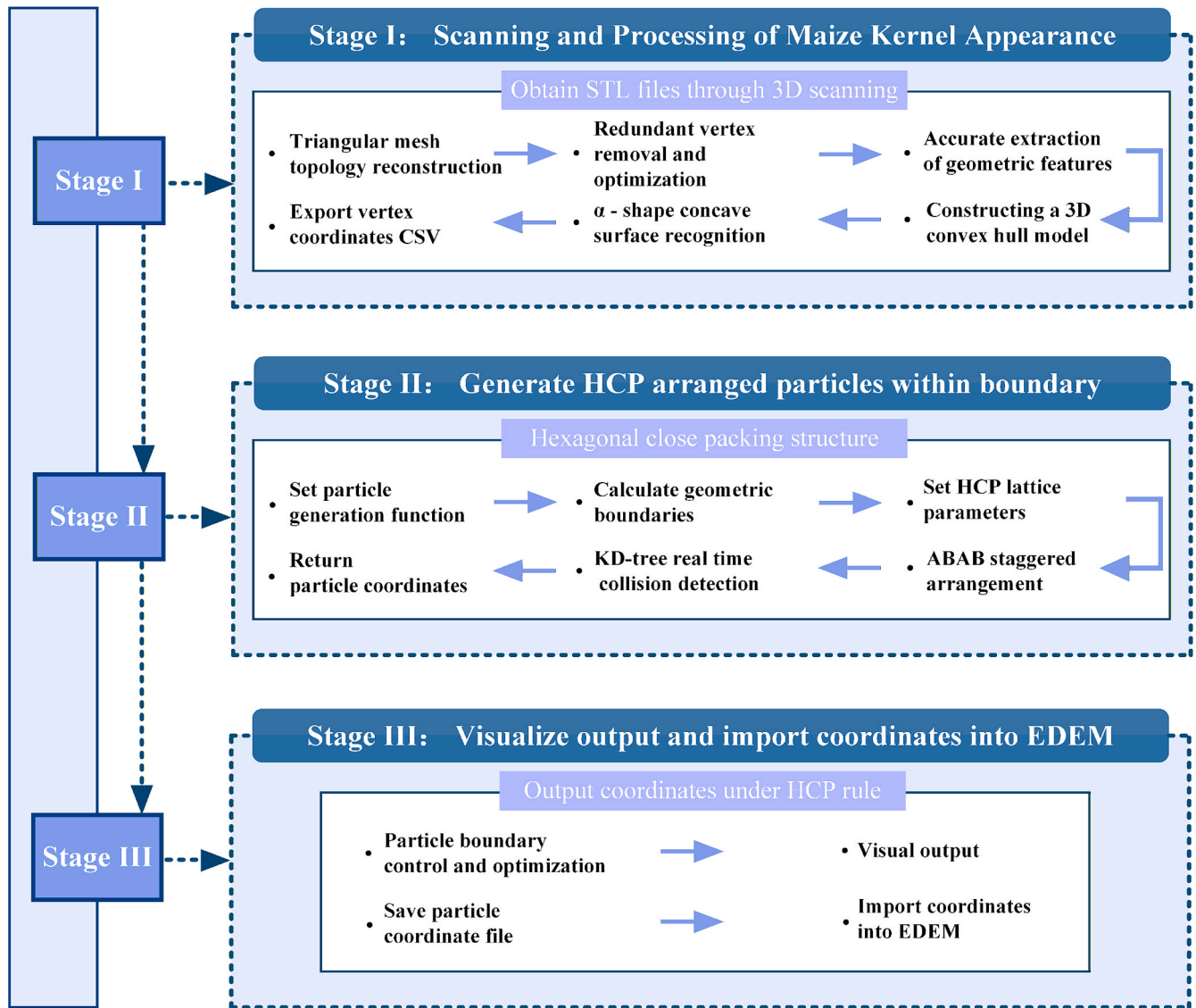


Fig. 3. HCP filling method and particle coordinate acquisition flowchart for maize kernel model.

2022 to establish a particle model for subsequent discrete element simulations. This model not only accurately reproduces the geometric morphology of maize kernels but also benefits from the compact arrangement rules of HCP, which can truly simulate the dense structure inside maize kernels, helping to more accurately reflect their fundamental mechanical properties in simulation and laying the foundation for the calibration of bonding parameters in the subsequent Bonding V2 model.

The particle radius directly affects the number of particles in the model, which, in turn, significantly impacts simulation accuracy and computational efficiency. This study established particle models for different radii (0.35 mm, 0.30 mm, 0.25 mm, and 0.20 mm), corresponding to a total number of particles of 816, 1,599, 2,806, and 5,478, respectively. As shown in Fig. 4, when the particle radius decreases from 0.35 mm to 0.20 mm, the simulation time increases gradually from 0.5 h to 5 h. The results show that as particle radius decreases, the number of particles required for modelling increases significantly, while simulation accuracy improves. However, computational time also increases considerably, leading to higher costs and greater demand on computational resources. Considering both accuracy and efficiency, this study ultimately selected particles with a radius of 0.25 mm for modelling and subsequent simulation experiments.

2.3. Uniaxial compression test and model validation method

Uniaxial compression testing plays a core role in the study of material mechanical properties. Through this test, compressive stress and strain data, along with the complete stress-strain curve of the material, can be obtained, and key mechanical parameters, such as the peak load and elastic modulus, can be derived (Hamann et al., 2006; Liu et al., 2018). This study utilized a texture analyzer developed by the SMS company in the UK, model X100-1 LC100/108797, with a detection accuracy of 0.01 N, to conduct compression tests. The aim was to systematically explore its mechanical response and fracture behavior under external loads.

The experiment focuses on evaluating the effects of various factors, including part type, moisture content, axial ratio, and loading direction, on the elastic modulus, load characteristics, and failure mechanism of maize kernels. Using a texture analyzer and its accompanying software, obtain key parameters, including the force-displacement curve, peak load, and fracture displacement, during compression. The experiment was conducted at a constant rate of 6 mm/min, with compression directions applied to the belly, side, and top of the kernel, as shown in Fig. 5. When the compression direction is towards the abdomen or side, the preload force is set to 2 N. Due to the relatively soft pedicle structure

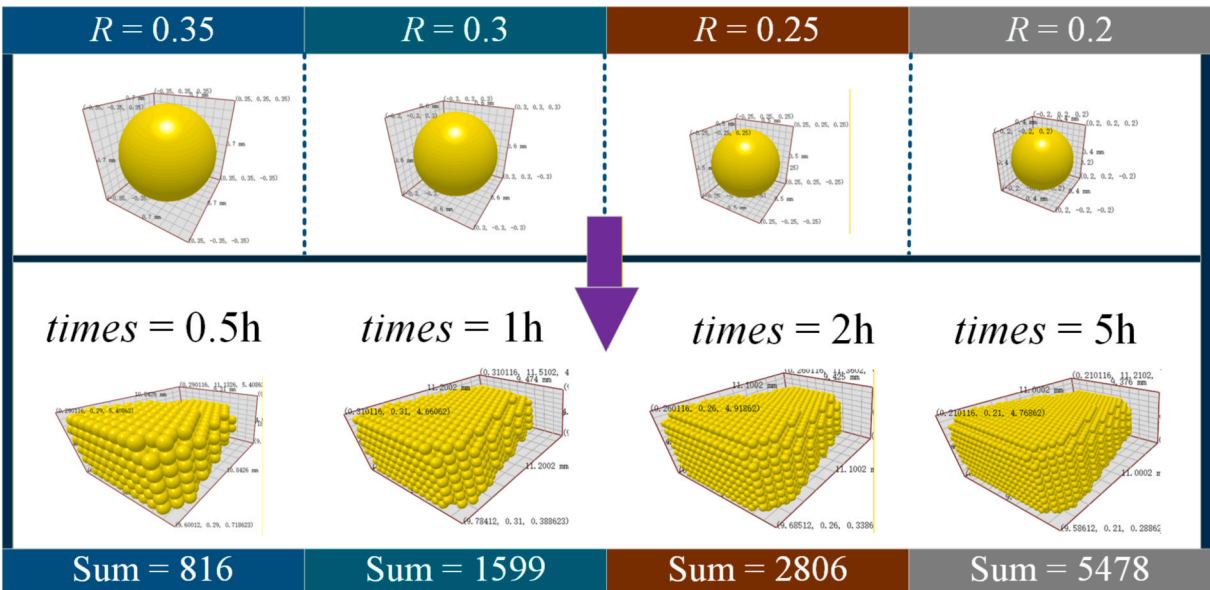


Fig. 4. The influence of different particle radii on simulation time and accuracy

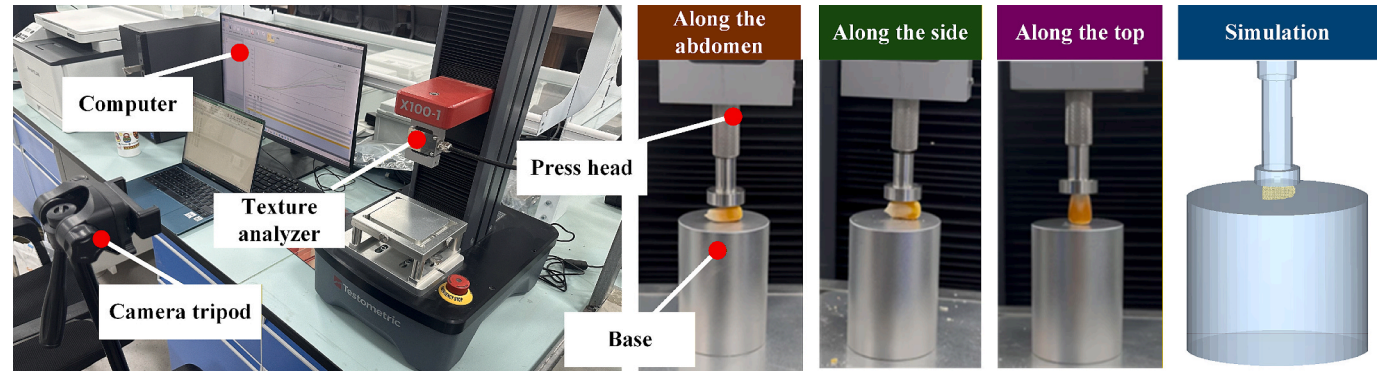


Fig. 5. Equipment and simulation required for uniaxial compression test

at the top of the kernel, the preload force is increased to 5 N. After the preload is complete, continue compressing to a depth of 3 mm, recording force and deformation data at each stage. Focus on the mechanical response characteristics of the elastic and plastic stages, as well as the mechanical behavior at the final fracture point. Select 20 maize kernels for each compression direction for testing. Specifically, the peak load directly characterizes the macroscopic compressive strength or failure threshold of the material under uniaxial compression. Whether the external load surpasses this internal bearing limit is the primary factor in causing mechanical damage during operations. At the same time, fracture displacement indicates the energy absorption capacity before failure and is a crucial measure for assessing the toughness of maize kernels, whose mechanical properties are greatly affected by moisture content. Additionally, as peak load is a common indicator in the mechanical analysis of various agricultural materials (Correa et al., 2007; Kruszelnicka et al., 2022; Omarov et al., 2012), such as corn, wheat, and rice, this study chooses both peak load and fracture displacement as key indicators to describe material mechanical responses in the upcoming model development and analysis.

To investigate the relationship between moisture content, kernel position, and axial ratio with load and displacement, samples with axial ratios ranging from 0.6 to 1.5 were selected for compression tests in different directions, with moisture contents of 9.1%, 16.4%, 20.8%, and 25.7%, respectively. For simulation, the EDEM2022 software was used; the computing platform is equipped with an Intel Core i9-13900HX

Table 1
Simulation parameters of the maize kernel model

Parameter properties	Type	Value
Poisson's ratio	kernel	0.4
	steel	0.3
Density (kg/m ³)	kernel	1178
	steel	7850
Elastic Modulus (Pa)	kernel	2.42×10^8
	steel	2.06×10^{11}
Recovery factor	kernel - kernel	0.25
	kernel - steel	0.65
Coefficient of static friction	kernel - kernel	0.25
	kernel - steel	0.40
Rolling friction coefficient	kernel - kernel	0.06
	kernel - steel	0.03
Normal stiffness per unit area (N/m ²)		8.9465E+09
Shear stiffness per unit area (N/m ²)		8.9465E+09
Normal strength		1.7485E+06
Shear strength		1.7485E+06
Bonded disk scale		1.2

processor with 28 physical cores (a total of 32 logical threads), 16GB of memory, and the Hertz-Mindlin BPM contact model and Bonding V2 model were employed. Taking the middle kernel as the research object, the pressure direction is set to the kernel's belly. The simulation process has a fixed time step of 3.2e-07s and a data storage interval of 0.01s. The

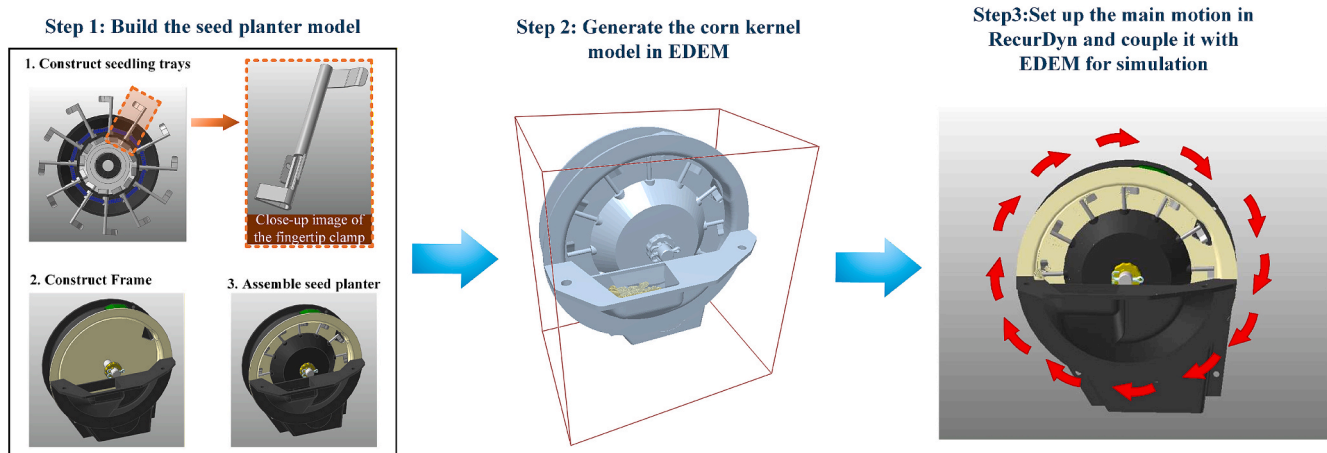


Fig. 6. Model construction and DEM-MBD coupling steps of the Mechanical seed metering device

model parameters are shown in Table 1.

This study was calibrated through extensive simulation experiments, including Normal/Shear Stiffness per unit area, Normal/Shear Strength, and Bond Disk Scale. Compared with the average peak load from the experiment, the simulated peak load error is 1.7%. In contrast, some studies have obtained maize kernel shapes and modeled them using reverse-engineering techniques, achieving a relative error of 3.2% between simulation and experimental results (Su et al., 2021). The effective reduction of errors in this study is mainly due to the high geometric accuracy of the established maize kernel model, which more realistically simulates the dense structure within the kernel and better characterizes its mechanical properties. Due to the absence of preloading force in the simulation, the fracture displacement is slightly greater by 0.1–0.2 mm than in the actual situation. However, the model can still effectively reflect the main mechanical response characteristics of the kernels, meeting the basic requirements of mechanical performance analysis.

As an important tool for characterizing the mechanical behavior of materials, scholars have developed constitutive models to predict the compression behavior of biomass materials, such as maize stover, using elastoplastic models (Kaliyan & Morey, 2009). Its high computational complexity limits its application in rapid modelling of agricultural materials (Xue et al., 2025). This study provides a data basis for

constructing constitutive models of kernel moisture content, axial ratio, peak load, and axial displacement under abdominal pressure, based on force-displacement curve data points. In the uniaxial compression simulation experiment, an orthogonal design is used, with peak load and displacement as indicators and calibration parameters as factors.

During the verification process, kernels with moisture contents of 10.4%, 15.7%, 19.2%, and 25.9% were prepared using the soaking method. Eight sets of samples were extracted, and the axial ratios were recorded. Substitute the moisture content and axial ratio as input parameters into the constitutive model to calculate the theoretical peak load and displacement. Combine these predicted values with response surface analysis to obtain the corresponding bonding parameter values. Based on existing modelling, these parameters are imported into the Bonding V2 model to obtain a complete force-displacement curve, and the model's accuracy is verified using peak load as an indicator. The parameter acquisition method will be further applied in mechanical seeding simulation to verify the rationality of parameter settings.

2.4. Application of the model in a mechanical seed metering device

During mechanical sowing, the gripping, conveying, rotating, and releasing actions of the fingers render seeds highly susceptible to surface

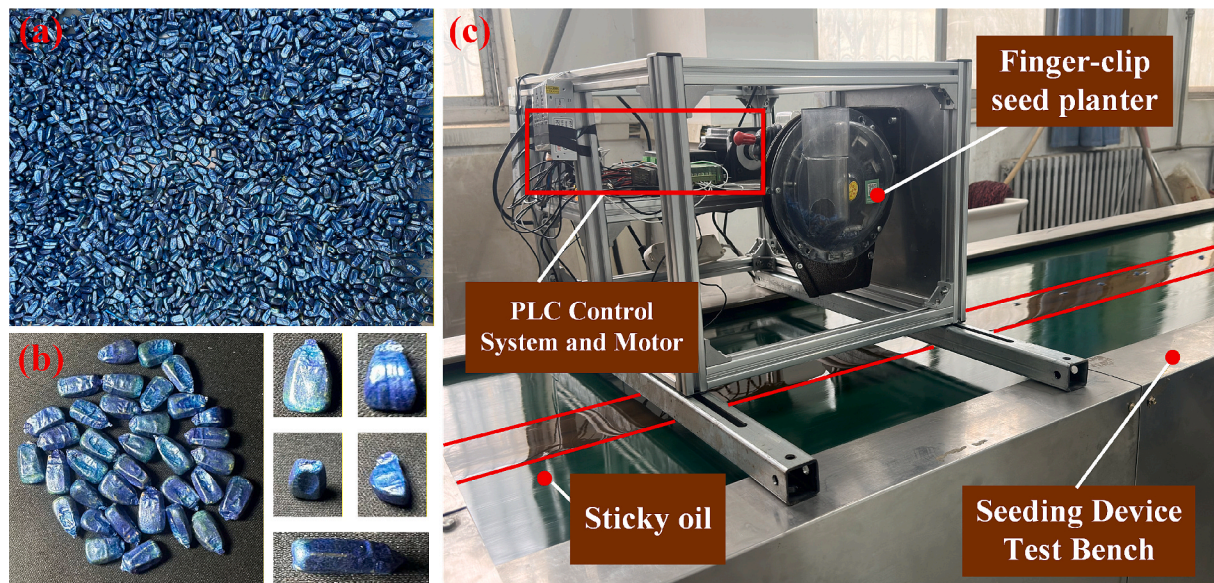


Fig. 7. Bench experiment of maize kernels coated with blue coating agent and a mechanical seed metering device. (a) Coat maize kernels with a coating agent (b) Detail image of the coated seeds (c) Test bench of mechanical seeder

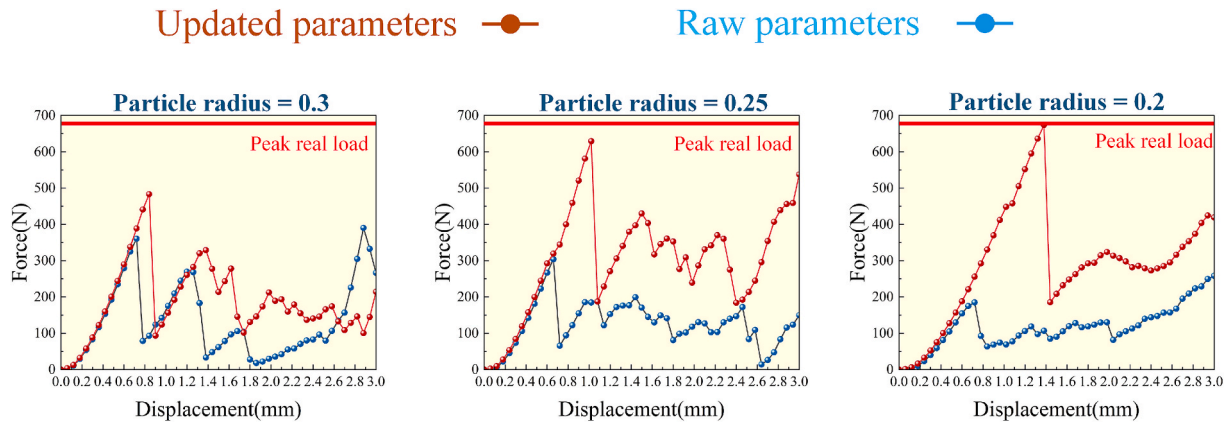


Fig. 8. Compression simulation test with different parameters

abrasion or even fracture, thereby severely compromising germination rates. To address this, the developed high-precision HCP maize kernel model, along with its calibrated bonding parameters, was applied to this practical scenario, and a coupled DEM-MBD co-simulation model was established. The model construction steps are shown in Fig. 6. A finger chuck model is constructed, with two end faces at an angle of 80° at the lower end of the finger chuck. The finger chucks are connected by tension springs passing through circular holes on the end faces. Each finger chuck has 12 finger chucks and 12 tension springs. Assemble the mechanical seed metering device rack and install the finger chuck. Import the complete model into EDEM 2022 and open the coupling interface. Apply torque to the input shaft in RecurDyn 2023 to drive the finger chuck. Based on differences in kernel location, 200 maize kernel models were generated: 10 at the top, 175 in the middle, and 15 at the bottom. In this study, location-specific differences among kernels are represented in the model solely through their unique axial ratios. At the same time, the corresponding bonding parameters are derived using the established constitutive model. Simulation focuses on analysing the physical processes that cause microscopic damage to seeds. By simulating the entire process of seed filling, carrying, and feeding of the mechanical seed metering device at a speed of 24 rpm, the average resultant force and distribution area generated by the finger clamp and seed are determined. Trays during clamping and pushing of maize kernels were quantitatively analyzed, enabling accurate assessment and model validation of potential mechanical damage to the kernels.

To investigate the damage characteristics of seeds during the actual sowing process, maize kernels with approximately 10% moisture content were selected for the experiment. They were evenly wrapped with a blue coating agent, as shown in Figs. 7(a) and (b). After natural air

drying, they were put into the sowing device for the experiment. The experimental setup is shown in Fig. 7 (c). The mechanical seed metering device is installed on the experimental platform, and a sticky oil belt collection device is set directly below its outlet to receive the discharged seeds. After the platform is started, the device's speed is controlled by the PLC program and set to three levels: 6 rpm, 12 rpm, and 24 rpm. The device's corresponding forward speeds are 2 km/h, 4 km/h, and 8 km/h. Record the wear of kernels and their coatings at different rotational speeds during the experiment.

3. Results and discussion

This study examined the impact of particle radius on bonding parameters through a combination of experiments and simulations. The relationship between intrinsic parameters and bonding parameters was quantitatively established using the maximum load and its displacement as the basis. The accuracy of finger clamping force and its correlation with kernel damage were verified through DEM-MBD coupling simulations.

3.1. Radius selection and parameter calibration update in particle modelling

When conducting uniaxial compression simulation experiments on kernels formed by modelling particles with different radii, if the same bonding parameters of the Bonding V2 model are used, the force-displacement curve should exhibit a consistent overall trend. However, as shown in Fig. 8, the simulation results indicate that different particle-size models not only exhibit differences in curve trends but also

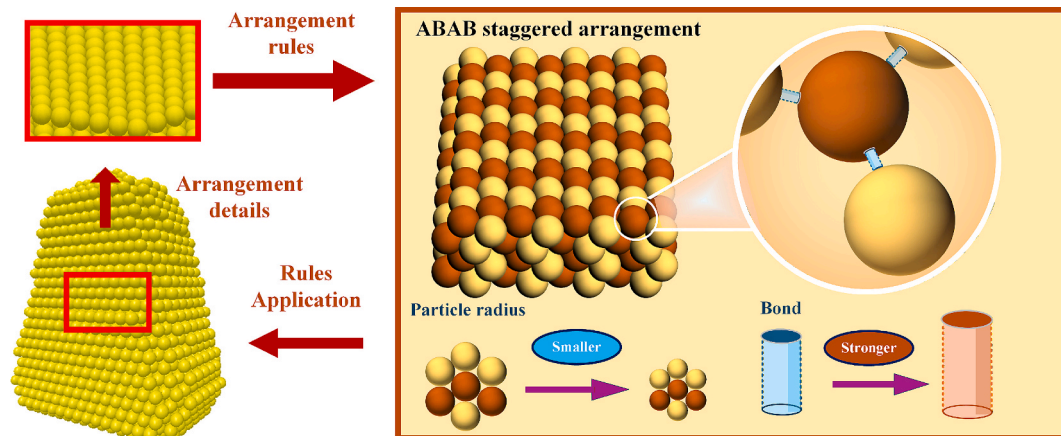


Fig. 9. Detail diagram of maize kernel modelling, HCP arrangement rules, and bond strength variation laws

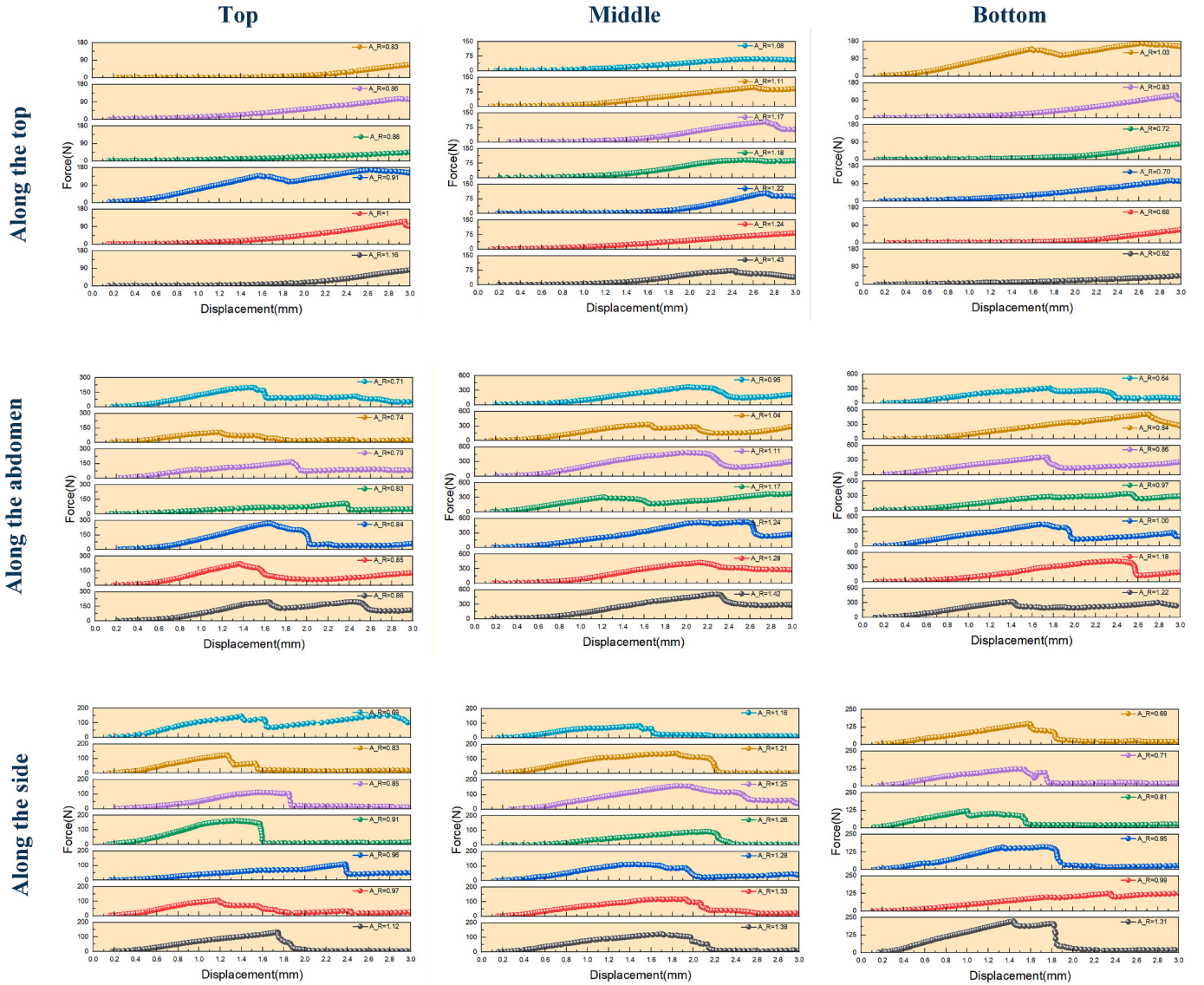


Fig. 10. Force-displacement curves of different axial ratios and pressure directions at a moisture content of 16.4%

display significant deviations in maximum load values, suggesting that changes in particle radius require recalibration of bonding parameters.

Based on the Bonding V2 model theory, we derive the parameter calibration law for variations in particle radius as follows. As shown in Fig. 9, in order to ensure that particle models with different radii have equivalent macroscopic mechanical responses in uniaxial compression, that is, generate the same macroscopic force under the same displacement and fail at the same macro level, it is necessary to ensure that the stress level of the bonding between particles remains consistent because the contact area A of the adhesive bond is proportional to the square of the particle radius. The bond stiffness, K , is proportional to the product of the stiffness parameter and the area ($K \propto \phi \cdot A$). To maintain a constant key stiffness, it is necessary to meet the following requirements $p_{\text{new}} \cdot A_{\text{new}} = p_0 \cdot A_0$. By substituting $A_{\text{new}} \propto (r_0/m)^2 = (\frac{1}{m})^2 A_0$, it can be concluded that the calibration law for shear stiffness n is the same. The parameter s represents the bonding radius coefficient, which is an intrinsic property of the material, and its dimension is independent of geometric dimensions.

Therefore, it should be kept constant. This derivation begins with the principle of mechanical similarity, clarifying the scaling law of stiffness parameters and the invariance of strength parameters. Moreover, draw the following conclusion: the parameters corresponding to the particle

with the current radius r_0 are p , n , and s . When the particle radius becomes r_0 / m , the corresponding parameters should be updated to $m^2 p$, $m^2 n$, and s . When the particle radius is 0.3 mm, 0.25 mm, and 0.2 mm, using peak load as the indicator, the model accuracy is 73.5%, 95.6%, and 98.5%, respectively, which are 22.1%, 51.5%, and 70.6% higher than the initial parameter accuracy. This result validates the effectiveness of the parameter calibration rule and provides a basis for selecting 0.25 mm as the modelling particle radius. Although the scaling law theoretically applies beyond the verification range of 0.2–0.35 mm, its practical application is limited by accuracy and computational cost. For particles with a radius greater than 0.35 mm, although it saves computational resources, the sharp reduction in the number of particles will compromise the geometric fidelity and mechanical accuracy of the kernel model, resulting in distorted force-displacement trends. Therefore, it is not recommended to extrapolate to larger radii. On the contrary, for a radius less than 0.25 mm, although the scaling law remains valid and accuracy has improved, the exponential growth in particle numbers makes large-scale simulations impractical. Therefore, given the balance between engineering accuracy and computational efficiency in simulating maize kernel damage, a particle radius of 0.25 mm is optimal. In comparison, a radius of 0.2 mm or smaller is recommended only for high-fidelity single-particle modelling.

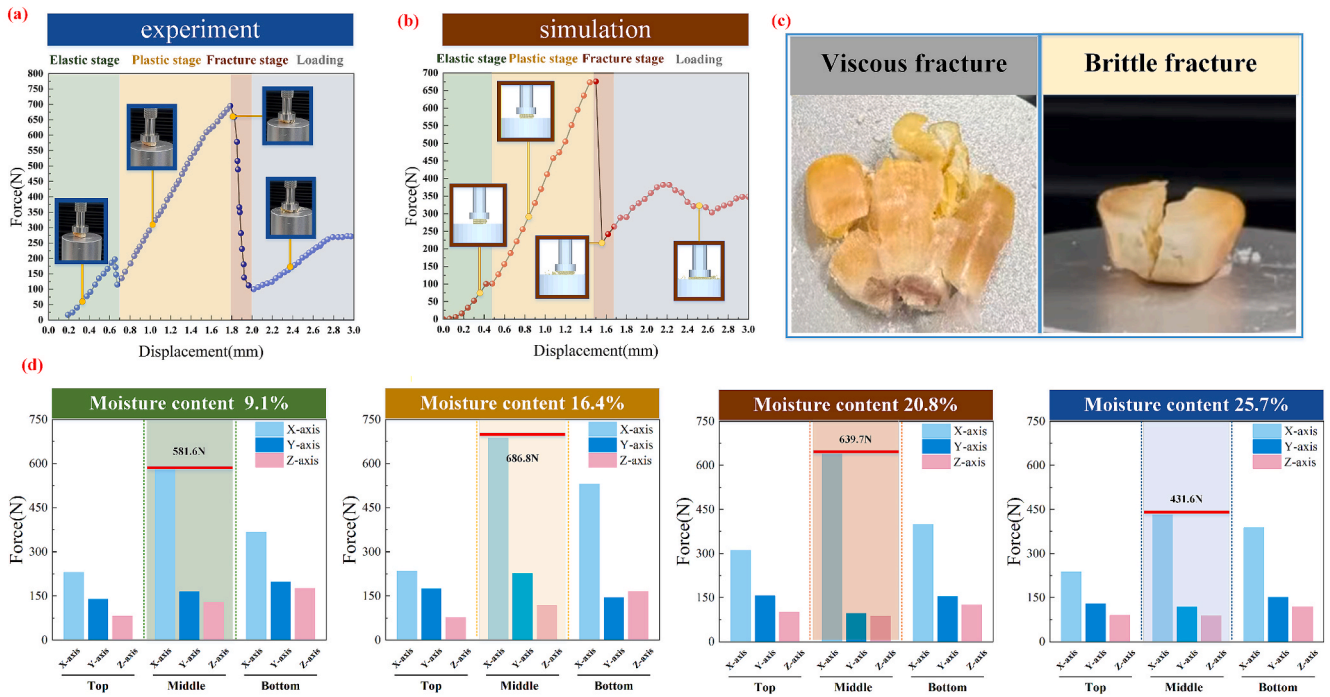


Fig. 11. Analysis of uniaxial compression test results. (a) Compression characteristics at each stage. (b) Simulation test results. (c) Compression characteristics of kernels with varying moisture contents. (d) Load values at different moisture levels, locations, and compression orientations.

3.2. Analysis of force-displacement curve results

From uniaxial compression tests, force-displacement diagrams were obtained for kernels under various moisture contents, axial ratios, and pressure directions. The results of the uniaxial compression test at a kernel moisture content of 16.4% are shown in Fig. 10.

The axial ratio distribution ranges for the first, middle, and bottom stage kernels are 0.7-1.2, 0.8-1.5, and 0.6-1.3, respectively. As the axial ratio increases, the geometric shape transitions from ellipsoidal to flat, and the initial contact area between the kernel and the probe of the texture analyzer becomes larger, gradually changing from line contact to surface contact. Within the deformation range of 0-0.5 mm, the slope of the stress-strain curve increases gradually, thereby enhancing the ability to resist deformation.

A high axial ratio typically correlates with large particle size, and as particle size increases, peak load rises, while fracture displacement increases. Under the same pressure direction, the force displacement curve shows a similar variation pattern: as the probe is loaded, the load continues to rise with increasing displacement, and the slope of the curve gradually increases; When loaded to the ultimate bearing state of the kernel, the kernel fractures and the load rapidly decreases. Under high-moisture conditions, the load does not drop sharply immediately after

fracture. Instead, it forms a yield plateau within the displacement range of 0.2-0.4 mm, where the load decreases gradually before falling rapidly. Afterward, due to residual strength in the kernels, the load continued to slowly increase with displacement until it reached 3 mm, at which point it ceased.

Maize kernels exhibit clear elastic-plastic mechanical responses during compression. As shown in Figs. 11(a) and (b), during the initial elastic stage, stress and strain are approximately linearly related. As the load increases, the material enters the plastic yield stage, where irreversible damage and internal microcrack propagation occur. After reaching peak strength, a macroscopic fracture occurs, and stress drops rapidly. As shown in Fig. 11 (c), high moisture content kernels form yield platforms before and after fracture due to water softening, and the stress only drops to 50% of the peak value after fracture, exhibiting ductile fracture characteristics; The low moisture content kernels suddenly fracture at a displacement of about 1.6 mm, with a sudden drop in stress to a peak of 25% and a flat cross-section, exhibiting brittle fracture.

As shown in Fig. 11 (d), the abdominal direction has the strongest load-bearing capacity, with a peak load of 500-600 N and residual stress of about 120 N; the side direction has a peak load of 150-180 N, showing brittle fracture and no residual stress; The peak load in the top direction is the lowest (75-120 N), but the fracture displacement exceeds 2.5 mm, forming a clear truncated zone and exhibiting progressive failure. There are also differences in the mechanical properties of kernels in different parts, and the average bearing capacity of middle kernels can reach up to 680 N, which is 127% and 31% higher than that of the top (300 N) and bottom (520 N) segments, respectively.

As mentioned earlier, the central grains account for 87.5% of the total number of ears, and their plump abdomens are also at high risk of mechanical damage. Considering that abdominal compression is a typical and critical working condition, and the central grains occupy an absolute numerical advantage in the population and have the strongest mechanical bearing characteristics, in order to maximize the representativeness and engineering application value of the model, the subsequent constitutive model construction, parameter calibration, and orthogonal experiments all selected the central grains in the direction of abdominal compression as the core research object. Based on this

Table 2
Constitutive model parameters

Parameter	Physical significance	The range of values
w	Measure water content	0.01-0.3
r_0	Measure the axis ratio	0.6-1.6
E_0	Reference modulus of elasticity	5-30
γ_0	Humidity sensitivity coefficient	1-8
αE	The correction factor of the axis ratio	-1-1
σ_{y0}	Benchmark yield stress	20-80
α	Yield stress humidity correction	-3-3
$\beta \sigma$	Yield stress axis ratio correction	0-3
τ_{10}	Baseline relaxation time	0.001-0.1
b	Relaxation time humidity correction	0-2
γ	Hardening coefficient humidity correction	0-0.3
$\delta \beta$	Hardening coefficient axis ratio correction	-5-5

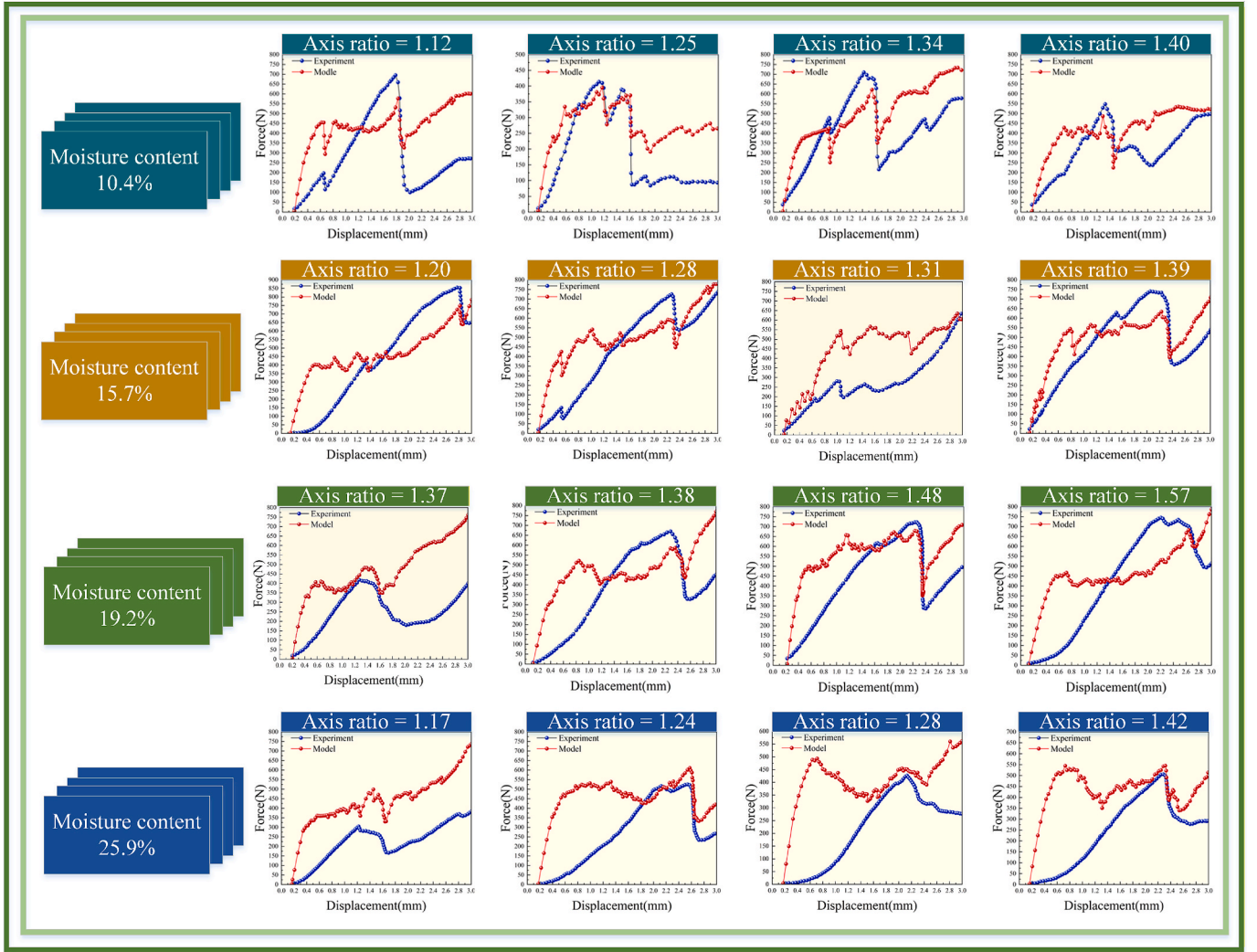


Fig. 12. Comparison diagram of the constitutive model and the experiment

condition, the elastic modulus of maize kernels can be estimated at approximately 242 MPa.

By recording data points on each curve, the data provide support for constructing a relationship model between peak load and displacement of maize kernels with different moisture contents and axial ratios in the future.

3.3. Inverse Identification of Constitutive Parameters of Maize Kernels

This study is based on the theory of elastic-viscoplasticity and develops a constitutive model that partially characterizes the complex mechanical behavior of maize kernels. This model describes the mechanical response of maize kernels through three interconnected mechanical component systems, which are divided into elastic, viscoelastic, and plastic stages. The parameters are listed in Table 2, and their specific values must be determined from experimental data.

The elastic component characterizes the recoverable deformation stage of maize kernels. Beyond the basic form of Hooke's law, this model incorporates moisture content and axial ratio r as key environmental and geometric variables to capture their significant influence on material stiffness. To accurately represent the behavior of heterogeneous biomass materials containing bound water—where apparent stiffness exhibits subtle nonlinear variations under larger strains due to mechanisms like micro-void closure and molecular rearrangement—the term $(1 - e^{-2\varepsilon})$ is introduced. The fundamental form of this expression is given by formula

(3.1):

$$\sigma_e = E_0 \cdot (1.5 - \gamma \cdot w) \cdot (1 + \alpha_E \cdot r) \cdot (\varepsilon - 0.01\varepsilon_0) \cdot (1 - e^{-2\varepsilon}) \quad (3.1)$$

Among them, the reference elastic modulus term $(1.5 - \gamma \cdot w)$ captures the plasticizing and softening effect of moisture on molecular bonds; The term $(1 + \alpha_E \cdot r)$ quantifies the modulation effect of particle geometry on strength: the larger the axial ratio, the higher the strength. The nonlinear term $(1 - e^{-2\varepsilon})$ is used to describe the nonlinear response under considerable strain.

The viscoelastic component, based on the Boltzmann superposition principle, is employed to characterize the time-dependent energy dissipation in maize kernels, specifically the stress-relaxation effect. Its response is formulated as a weighted superposition of historical stress increments, with weighting factors that decay exponentially with the relaxation time τ . Based on experimental data, the relaxation time τ correlates strongly with moisture content, as defined by formula (3.2).

$$\sigma_v(t) = \sum_{i=1}^t \left(\frac{\Delta \sigma_{e,i}}{\Delta t} \cdot e^{-(t-t_i)/\tau} \right) \cdot e^{-(2\varepsilon + 5\varepsilon_p)} \quad (3.2)$$

The plastic component governs the material's yield and fracture behavior. To accurately reproduce the experimentally observed yield plateau and stress-drop phenomena, this study adopts a constitutive formulation expressed as the product of a saturation-type hardening function and a strain-softening function, as detailed in formula (3.3).

Table 3
Test design and results

Run	Factors			Response index	
	p	n	s	R_1	R_2
1	8.9465E+09(0)	1.7485E+06(0)	1.2(0)	633.432	0.96
2	8.9465E+09(0)	2.064E+06(+1)	1.1(-1)	978.351	2.58
3	8.9465E+09(0)	2.064E+06(+1)	1.3(+1)	1306.49	3
4	8.9465E+09(0)	1.433E+06(-1)	1.1(-1)	501.204	0.84
5	8.9465E+09(0)	1.7485E+06(0)	1.2(0)	633.658	0.96
6	7.333E+09(-1)	2.064E+06(+1)	1.2(0)	1202.17	2.82
7	1.056E+10(+1)	1.7485E+06(0)	1.1(-1)	581.144	0.9
8	1.056E+10(+1)	2.064E+06(+1)	1.2(0)	1370.76	3
9	1.056E+10(+1)	1.433E+06(-1)	1.2(0)	669.27	1.14
10	7.333E+09(-1)	1.7485E+06(0)	1.1(-1)	614.058	2.82
11	8.9465E+09(0)	1.7485E+06(0)	1.2(0)	633.658	0.96
12	8.9465E+09(0)	1.433E+06(-1)	1.3(+1)	729.037	1.02
13	8.9465E+09(0)	1.7485E+06(0)	1.2(0)	633.658	0.96
14	7.333E+09(-1)	1.7485E+06(0)	1.3(+1)	1008.41	3
15	7.333E+09(-1)	1.433E+06(-1)	1.2(0)	535.381	0.9
16	1.056E+10(+1)	1.7485E+06(0)	1.3(+1)	831.267	1.08
17	8.9465E+09(0)	1.7485E+06(0)	1.2(0)	633.581	0.96

$$\sigma_p = \sigma_y \cdot (1 - e^{-\beta \sqrt{\epsilon_p}}) \cdot \eta(\epsilon_p) \quad (3.3)$$

Among them, the $1 - e^{-\beta \sqrt{\epsilon_p}}$ term simulates the plastic hardening process, while the function $\eta(\epsilon_p)$ is defined as the switching function that undergoes a transition from hardening to softening at the critical strain, which is controlled by the moisture content. To observe elastic strain, plastic yield, and other phenomena in maize kernels under uniaxial compression, this paper superimposes the corresponding stresses. The fundamental form of this constitutive expression is given by formula (3.4):

$$\sigma_t = \sigma_e + \sigma_v + \sigma_p \quad (3.4)$$

Four sample groups with specific moisture contents (10.4%, 15.7%, 19.2%, and 25.9%) were prepared by soaking the same batch of maize kernels. It should be noted that this batch of samples is independent of the dataset used to construct the model in the previous section and is specifically used for subsequent validation. Based on the measured axial ratios for each sample group, the moisture content and axial ratio were

used as inputs to the established mathematical model, and the theoretical force-displacement curve was plotted. The peak load and corresponding fracture displacement were predicted. Finally, by conducting uniaxial compression tests on the batch of samples, the experimentally measured force-displacement curve was obtained for comparison and verification against the theoretically predicted values.

Compared with the model's predicted results, as shown in Fig. 12, the Model predictions indicate that in the initial elastic stage, the theoretical curve rises significantly faster than the experimental curve, but gradually approaches the actual load value before fracture. As the moisture content increases, the axial ratio decreases, and the initial slope of the graph decreases accordingly, reflecting the decrease in elastic modulus at high moisture content. On the other hand, as the axial ratio increases, the contact between the kernel and the indenter gradually changes from linear contact to surface contact, and the characteristic elastic modulus increases accordingly, thereby increasing the peak load at fracture. The model's prediction of fracture displacement is relatively accurate, indicating that the two intrinsic parameters, moisture content and axial ratio, effectively reflect the peak load and fracture displacement of maize kernels during compression, which are key mechanical performance indicators.

3.4. Single-factor simulation experiment and model validation

To investigate the influence of parameters in the Bonding V2 model on the peak load and displacement in uniaxial compression tests, this paper conducted single-factor uniaxial compression simulations using peak load (R_1) and displacement (R_2) as response indicators. The experimental factors are as follows: Normal/Shear Stiffness per unit area (p), Normal/Shear Strength (n), and Bond Disk Scale (s). The experimental design and results are shown in Table 3, and the analysis of variance results are presented in Table 4.

The P -values for the quadratic regression model are all less than 0.01, indicating that the fitted quadratic regression equation accurately reflects the relationship between the various factors and the response indicators. However, the contribution and interaction relationships of each factor with different response indicators vary. For the maximum load value (R_1), the order of significance is $s > p > n > p-n > p-s$, and

Table 4
Variance analysis of Maximum load value (R_1) and corresponding displacement (R_2)

Evaluation	Source	Sum of Squares	df	Mean Square	F-value	P-value
Maximum load value F/N	Model	1.661E+05	9	18457.21	249.47	< 0.0001***
	p	52393.76	1	52393.76	708.17	< 0.0001***
	n	6196.07	1	6196.07	83.75	< 0.0001***
	s	1.054E+05	1	1.054E+05	1424.73	< 0.0001***
	pn	1510.53	1	1510.53	20.42	0.0027***
	ps	497.40	1	497.40	6.72	0.0358***
	ns	12.21	1	12.21	0.1651	0.6967
	p^2	16.49	1	16.49	0.2228	0.6521
	n^2	81.15	1	81.15	1.10	0.3298
	s^2	3.34	1	3.34	0.0451	0.8379
	Residual	517.89	7	73.98		
	Lack of Fit	517.85	3	172.62	17867.87	< 0.0001
	Total	1.666E+05	16			
	Model	0.1435	9	0.0159	13.78	0.0011***
Corresponding displacement value D/mm	p	0.0288	1	0.0288	24.89	0.0016***
	n	0.0112	1	0.0112	9.72	0.0169**
	s	0.076	1	0.076	65.72	< 0.0001***
	pn	0.0036	1	0.0036	3.11	0.1211
	ps	0.0000	1	0.0000	0.0000	1.0000
	ns	0.0009	1	0.0009	0.7778	0.4071
	p^2	0.0059	1	0.0059	5.12	0.0582*
	n^2	0.0116	1	0.0116	10.03	0.0158**
	s^2	0.0059	1	0.0059	5.12	0.0582*
	Residual	0.0081	7	0.0012		
	Lack of Fit	0.0081	3	0.0027		
	Total	0.1516	16			

Note: *** is Extremely Significant ($p < 0.01$), ** Significant ($0.01 < p < 0.05$), * More Significant ($0.05 < p < 0.1$).

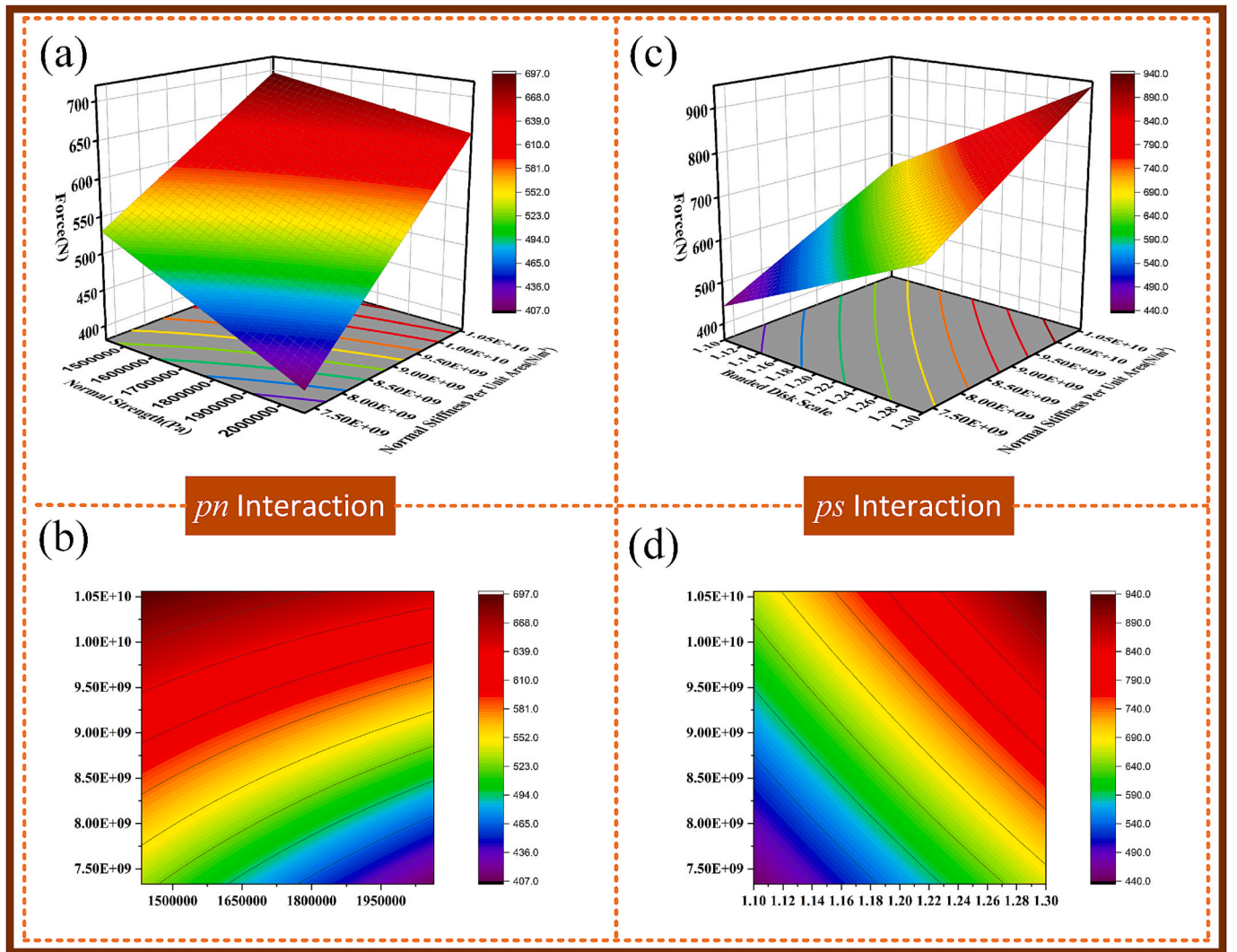


Fig. 13. Response surface analysis results of operational parameter optimization. (a) Response surface diagram of pn interaction (b) Contour map of pn interaction (c) Response surface diagram of ps interaction (d) Contour map of ps interaction

there is an interactive relationship between p and n , p and s , as shown in Fig. 13. As p and s increase and n decreases, the maximum load value significantly increases. The encoding regression model for the maximum load value can obtain the regression equation for force from formula (3.5):

$$R_1 = +543.2 - 8.6e^{-08}p - 4.74e^{-04}n + 646.40s + 3.82e^{-14}pn + 6.91e^{-08}ps \quad (3.5)$$

For the fracture displacement value (R_2), its significance order is $s > p > n^2 > n$. The following equation can obtain the corresponding encoding regression model for the displacement value (3.6):

$$R^2 = -3.31 - 1.176e^{-10}p - 1.77e^{-06}n + 9.14s + 5.274e^{-13}n^2 \quad (3.6)$$

Extract eight sets of sample data from kernels with moisture contents of 10.4%, 15.7%, 19.2%, and 25.9%. Substitute the moisture content and axial ratio as input parameters into the constitutive equation to calculate the theoretical peak load and displacement. Substitute it into formula (3.5) and formula (3.6), combining it with the parameter correspondence shown in Fig. 13 to obtain the corresponding simulation parameter values p , n , and s . Based on existing modelling, these parameters are imported into the Bonding V2 model, and a complete force-displacement curve is obtained through simulation. The peak load is then extracted as an indicator for verification.

To verify the accuracy of the model, uniaxial compression tests were conducted on the eight sets of kernel samples mentioned above to obtain actual force-displacement curves. Using peak load as the indicator, as

shown in Fig. 14, the results indicate that the error between the model's predicted value and the experiment's measured value is controlled within 4.5%. Currently, predicting kernel fracture behavior is a key research focus. Scholars have introduced a combination structure model and achieved prediction results with a relative error within 7.5% (Li et al., 2025); Another study predicted kernel fracture under abdominal posture impact conditions with an error of 2.7% (Yu et al., 2025); In addition, the error in predicting kernel damage based on machine learning methods is about 6% (Qiao et al., 2026).

The peak load in this study indicates the occurrence of fracture behavior and can therefore also be considered as a prediction of fracture behavior. Through error comparison, it is demonstrated that this study is effective in predicting kernel breakage. Currently, research on the accuracy of modelling and calibration of bonding parameters primarily focuses on maize stover. Previous studies have shown that the error between the uniaxial compression results and actual values after modelling and calibrating the bonding parameters of maize stover is 5.4% (Chen et al., 2025); In the numerical simulation of compression fracture of maize stover, the error is 7.8% (Zhang et al., 2020) The relative error of the prediction result for straw shear force is 2.8% (Che et al., 2024). In contrast, the relative error of this study is 1.7%, further verifying the reliability of kernel modelling and bonding parameter calibration. Based on the above analysis, the model can effectively predict the true mechanical properties of maize kernels under different

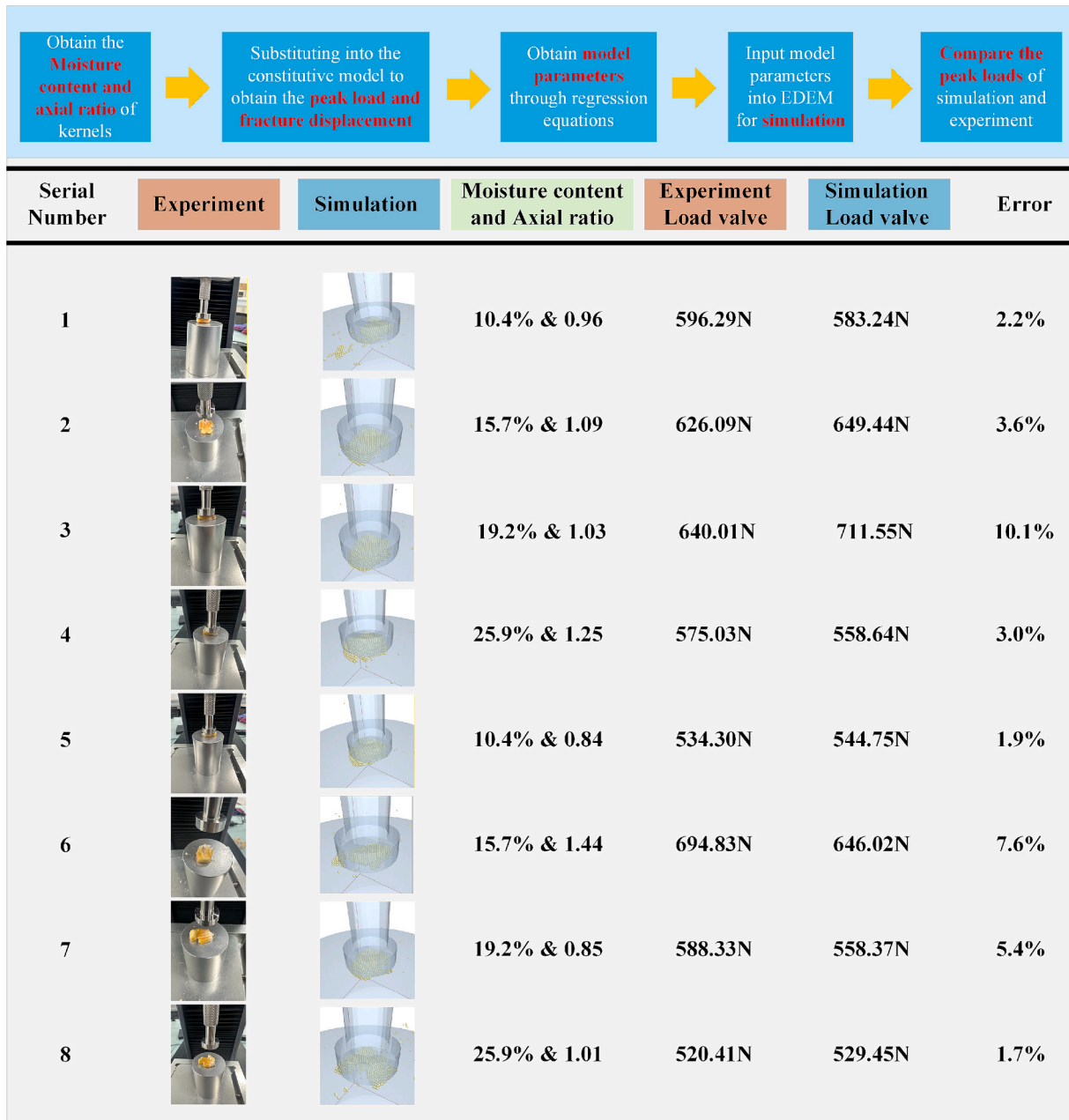


Fig. 14. Parameter calibration and model validation

moisture content and axial ratio conditions.

3.5. Application of the model in the mechanical seed metering device

This study applied the above model to the seeding process of a mechanical seed metering device. Given the low moisture content of maize kernels at sowing, a batch of samples with approximately 10% moisture content was prepared. After calculating the axial ratio, the corresponding bonding parameters were obtained by inputting it into the model for DEM-MBD coupling simulation. The wear of seeds during seeding by the device is illustrated in Fig. 15. The experimental results indicate that the device's rotation speed has a significant impact on seed wear, with higher rotation speeds resulting in greater wear. Specifically, as the rotational speed increases from 6 rpm to 24 rpm, the detachment of the blue coating agent from the kernels' surfaces increases, and it peels off in a sheet-like manner at high speeds. Additionally, the degree of damage is closely related to the kernel's axial ratio, and kernels with a

larger axial ratio exhibit more pronounced coating shedding. The damaged areas exhibit a regular distribution, primarily in the kernels' abdomens, while slight scratches are observed at the edges of the kernels.

The simulation results of DEM-MBD coupling are shown in Fig. 16. According to the working process of the mechanical seed metering device, it can be divided into six stages: Stage I is the stage of kernel input into the device, and Stage II is the stage of the kernel entering the finger clamping range. In these two stages, the kernels are in free movement, subjected only to mutual compression caused by rotational motion and to interaction with contact surfaces, with an average resultant force of approximately 0.04 N.

At this stage, there is no damage to the kernel surface, and all bonds in the simulation remain intact. In Stage III, the finger clamp transitions from an open to a closed position. During clamping, the joint force between the finger clamp and the seed tray gradually increases from 0.04 N to about 1 N, causing minor scratches on the seed surface, which

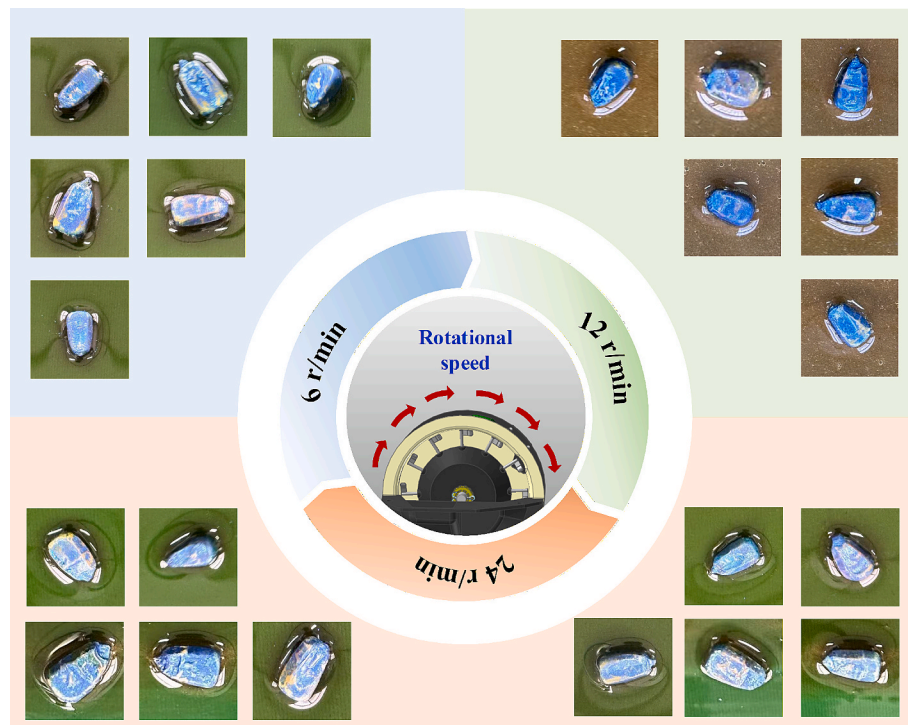


Fig. 15. Kernel wear under different speeds.

corresponds to a bond fracture rate of 0.48% in the simulation. Stage IV refers to the process of carrying the seeds and rotating them by 40° after the clamp is completely closed. During this stage, the damage is most significant, with the surface showing patchy damage. The average resultant force on the kernel reaches 1.03 N, and the bond fracture rate reaches 2.94%. In Stages V and VI, the average resultant force on the kernels was 0.87 N and 0.83 N, respectively, and the bond fracture ratio decreased to 0.45% and 0.15%, with slight surface scratching. Previous studies (Zhou & Qian, 1986) have reported that the finger clamping force in mechanical seeders is approximately 1 N. In this study, physical measurements with a tension meter at the same finger-opening angle yielded a consistent value of 1 N. This result closely aligns with the simulated force range of 0.83–1.03 N observed during Stage III to Stage VI, thereby confirming the effectiveness and accuracy of the proposed model.

Since the fracture of bonding bonds represents microscopic damage that manifests macroscopically as surface abrasion, the simulation results indicate that mechanical damage to seeds is most severe during Stage IV of the seeding process. This phase, occurring immediately after finger closure, is characterised by the maximum force exerted on the seed and the highest bond fracture rate, thereby constituting a critical control point for minimising damage. Although initial damage occurs during the transition phases—specifically the finger approaching and closing range (Stages I–II) and the subsequent release phase (Stages V–VI)—is relatively minor. This study systematically investigates the influence of the seeding device's operational stages on seed mechanical behaviour, providing a simulation-based basis for the structural optimisation of metering devices to maximise operational integrity.

The main innovation of this study is the proposal of a novel crop modelling method. This method can not only precisely reproduce the kernel shape but also effectively characterize its internal mechanical properties and establish a correlation between the bond fracture in the model and the actual damage behavior of the kernel. A method for determining bonding parameters based on intrinsic parameters, such as maize kernel moisture content and axial ratio, has been established. Without the need for uniaxial compression testing, theoretical force-

displacement curves can be obtained, not limited to predicting fracture load values. This bonding parameter can be effectively used to simulate mechanical seeding operations.

The main goal of this study is to develop a universal modelling framework that links “intrinsic parameters, mechanical response, bonding parameters” to measure how moisture content and axial ratio influence the peak load and fracture displacement of maize kernels. This framework creates a connection between physical attributes and simulation parameters and is theoretically applicable to maize samples from various sources. To maintain consistency in parameter calibration, maize varieties were kept constant during the experimental phase.

However, this study has certain limitations. The current experiments focused solely on maize kernels and have not yet been extended to other monocot crops, which are characterized by a uniform texture and lack internal voids. Additionally, for samples with moisture contents significantly outside the scope of this study, such as fresh-eating maize with a moisture content of 50%–60% (Wang et al., 2019), which is highly prone to damage, directly applying the proposed model may lead to considerable uncertainty and reduce predictive accuracy. Additionally, the established constitutive model exhibits a steep slope in the initial stage of the curve, and the simulation results in the elastic stage require improvement. The stress rise process after fracture also requires further optimization. The variance analysis results for the peak load (R_1) model in Table 4 show that the P-value for the “mismatch term” is less than 0.0001, indicating a statistical mismatch. However, the current model meets the requirements of engineering applications in terms of prediction accuracy. Research on the mechanical seed metering device still needs further development, and the model's application in other mechanized operation scenarios also requires expansion.

It is important to note that, in the current study, contact parameters were treated as fixed values independent of moisture content. To further enhance the model's generalizability under extreme moisture variations, future work will incorporate these contact parameters into a multi-factor calibration framework. Building on this, future research will extend the discrete element modelling methodology introduced in this study to other crops, such as homogeneous monocotyledonous species like rice and wheat, and broaden its application to various operational scenarios,

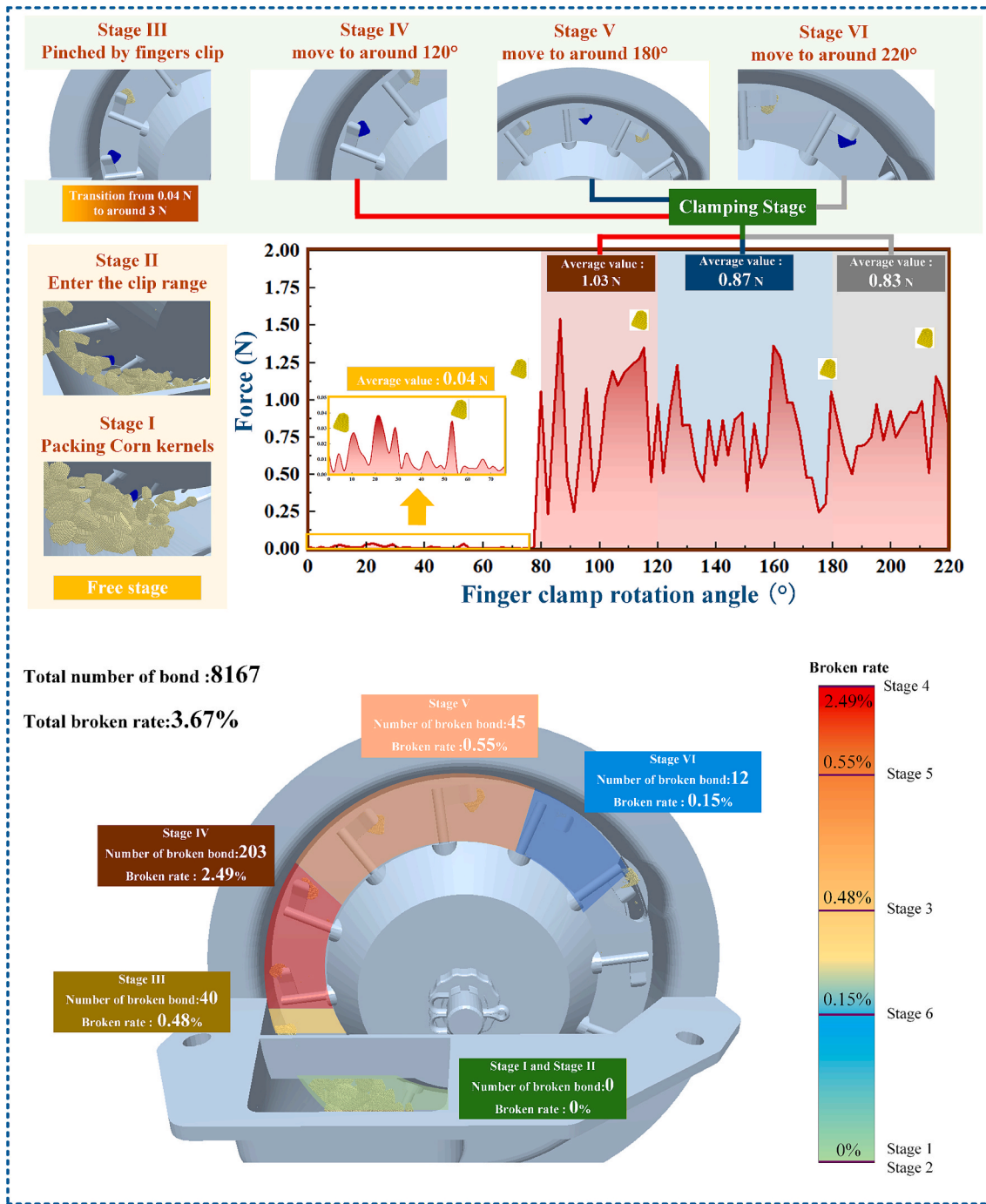


Fig. 16. Relationship between clamping force and wear during seed handling

including long-distance transport, threshing, and cleaning. This integrated approach will provide more systematic theoretical support for the high-fidelity DEM modelling of agricultural materials and the optimization design of machinery.

4. Conclusions

Addressing the critical issue of reduced germination rates and yields in maize kernels caused by mechanical damage during harvesting, transportation, and sowing, this paper proposes a novel discrete element method (DEM) modelling approach based on the HCP structure and high-precision geometric reconstruction. By using peak load and displacement as calibration bridges, the study establishes a quantitative

framework that links intrinsic parameters (moisture content and axial ratio) to DEM bonding parameters, thereby providing a high-fidelity model. Furthermore, it systematically executes the entire research workflow, from model construction and parameter calibration to experimental verification and simulation of the seeding process. The principal conclusions are as follows:

(1) The arrangement method of the HCP structure is tightly regular, which can better reflect the true mechanical properties of the kernels. The constructed model not only has a height close to that of a real kernel in appearance, but its force-displacement curve after compression and crushing also matches the experimental results, with a peak-load error of 1.7%.

(2) We comprehensively investigated the effects of moisture content,

axial ratio, and pressure direction on the maximum load value. We established a constitutive relationship between the maximum load value of the middle kernel and moisture content, as well as axial ratio, under the condition of using the abdomen as the pressure direction. At the same time, we optimized the operating parameters.

(3) Based on the Hertz Mindlin and Bonding V2 models, this article also derived the relationship between the maximum load value and its corresponding displacement and bonding parameters, including Normal/Shear Stiffness per unit area, Normal/Shear Strength and Bond Disk Scale. A quantitative correlation was established between physical intrinsic parameters such as moisture content and axial ratio, as well as bonding parameters, using the maximum load value as the bridge. The model's relative error was 4.5%.

(4) Through the seeding experiment of the mechanical seed metering device and the coupling simulation of EDEM and RecurDyn, the stress and damage degree of the seeds at different stages of the finger clamp were obtained. Among them, rotating the seeds by 40° after the finger clamp was completely closed caused the most significant damage to the seeds, with an average force of 1.03 N and a bond fracture rate of 2.94%.

CRediT authorship contribution statement

Jiu Liu: Writing – original draft, Validation, Software, Data curation, Conceptualization. **Rui Zhang:** Writing – original draft, Validation, Data curation. **Guibin Chen:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Funding acquisition, Formal analysis. **Fuzeng Yang:** Software, Resources, Methodology, Funding acquisition. **Zhijie Liu:** Supervision, Software, Resources, Project administration. **Zhengdao Liu:** Validation, Resources, Investigation, Formal analysis, Data curation. **Yongfei Sun:** Methodology, Investigation, Formal analysis, Conceptualization. **Qingjie Wang:** Resources, Project administration, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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