

CONSTRUCTION AND PARAMETER CALIBRATION OF A DISCRETE ELEMENT MODEL OF BARLEY SEEDLING STEMS

大麦苗茎秆离散元模型构建与参数标定

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ABSTRACT

To address the issue of insufficient parameters in the simulation of processes such as barley seedling stem harvesting using the discrete element method, this study focused on barley seedling stems of the Plante variety. Based on EDEM software, rigid (Hertz-Mindlin no slip model) and flexible (Hertz-Mindlin with bonding model) discrete element models were established. Combined with the results of physical tests, including the angle of repose (20.42°) and the average maximum load of three-point bending (2.62 N), parameters were screened and optimized through tests such as Plackett-Burman. The results showed that under the optimal contact parameter combination of the rigid model, the simulated average angle of repose was 20.31° , with an error of 0.78% compared to the physical test. For the flexible model, under the optimal bonding parameter combination, the simulated maximum bending stress was 2.64 N, with an error of 0.76% compared to the three-point bending test, verifying the accuracy of the models. The study indicated that the established models and parameters can accurately reflect the physicommechanical properties of barley seedling stems, providing a theoretical basis for the design and optimization of their harvesting, conveying, and processing machinery.

摘要

针对离散元法仿真大麦苗茎秆收获等过程时参数缺乏等问题,以普兰特品种大麦苗茎秆为对象,基于 EDEM 软件建立刚性 (Hertz-Mindlin no slip 模型) 与柔性 (Hertz-Mindlin with bonding 模型) 离散元模型,结合堆积角 (20.42°) 和三点弯曲平均最大载荷 (2.62N) 物理试验结果,通过 Plackett-Burman 等试验筛选优化参数。结果显示:刚性模型最优接触参数组合下,仿真平均堆积角 20.31° ,与物理试验误差 0.78%;柔性模型最优粘结参数组合下,仿真最大弯曲应力 2.64N,与三点弯曲试验误差 0.76%,验证了模型准确性。研究表明,所建模型及参数可准确反映大麦苗茎秆物理力学特性,为其收获、输送及加工机械的设计优化提供理论依据。

INTRODUCTION

Barley seedlings refer to the tender stems and leaves of barley before the jointing stage. The extract obtained after processing and extraction has medicinal effects such as lowering blood pressure, regulating blood lipids, antioxidation, and enhancing immunity (Zheng et al., 2017; Lu et al, 2019). The nutritional value is optimal when the plant height is 8-15 cm. At present, barley seedlings are usually harvested with low stubble, which easily leads to knife blocking, so there is no special harvesting machinery. However, due to the characteristics of high toughness, high moisture content, and hollow interior of barley seedling stems, it is difficult to clamp and has poor accuracy when obtaining mechanical parameters through existing traditional tests. Therefore, using the discrete element method to calibrate parameters of barley seedlings can shorten the test time, provide more accurate model parameters for harvesting simulation, and is of great significance for improving and optimizing the harvesting device.

In recent years, many scholars at home and abroad have used the discrete element method to calibrate the material properties of various crops in the field of agricultural engineering (Wu et al., 2022; Li et al, 2011; Zeng et al., 2021). Zhang Jiaxi et al. (2024) established a discrete element model for cotton straw in Xinjiang, and calibrated the simulation parameters through material property tests and virtual simulation tests.

The results showed that the cotton straw model and the calibrated discrete element simulation parameters are reliable. Wang Faan et al. (2024) established a discrete element model of Panax notoginseng rhizomes using 3D scanning modeling technology and EDEM, and formed a composite model with soil.

The working effect was tested through simulation tests with different types of excavating shovels. *Xia Hongmei et al. (2024)* first simplified hydroponic Chinese kale stems into transversely isotropic elastic bodies, and combined axial compression, three-point bending tests with ANSYS/LS-DYNA simulation, providing a reference finite element simulation method and parameter system for the optimization of cutting mechanisms of domestic hydroponic leafy vegetable harvesting machinery. *Chen et al., (2024)*, first established a discrete element model of alfalfa stems at the early flowering stage, and carried out contact parameter calibration research using EDEM software based on the Hertz-Mindlin (no-slip) contact model, providing a reference parameter system and calibration method for the discrete element simulation of forage harvesting machinery. To sum up, the current objects of parameter calibration for discrete element simulation at home and abroad are mainly fruits, seeds, and stems (*Liu et al., 2018; Zhang et al., 2022; Zhang et al., 2024*) and there are few studies on establishing discrete element models for flexible crops.

To establish a flexible discrete element model of barley seedlings (*Hou et al., 2020*), this paper takes barley seedlings as the research object. Based on the mechanical properties of barley seedlings, using EDEM discrete element simulation software, discrete element rigid and flexible models of barley seedling stems are established respectively based on Hertz-Mindlin (no slip) and Hertz-Mindlin with bonding contact models. Combined with the physical test of the angle of repose of barley seedling stems, as well as Plackett-Burman test, steepest ascent test, and Box-Behnken test, the comparative analysis of material property tests and simulation tests on barley seedlings before the jointing stage is carried out to verify the reliability of the model, providing a theoretical basis and reference for the design and optimization of subsequent barley seedling harvesting, conveying, and processing machinery.

Determination of Intrinsic Parameters of Barley Seedling Stems

Basic Parameters

The barley seedlings used in the experiment were from seeds of the French "Plante" variety, which were cultivated at room temperature until reaching a height of 15-20 cm and were harvested before the jointing stage. The collected barley seedlings were free of diseases, pests, and mechanical damage. After multiple measurements and calculations, the basic physical property parameters obtained were as follows: the average length of harvested stems was 180 mm, the stem diameter was 1.8 mm, the density was 125 kg/m³, and the moisture content was 73.4%.

Contact Physical Parameters

The physical parameters to be measured for establishing the discrete element model of barley seedling stems include Poisson's ratio, shear modulus of barley seedlings, as well as static friction coefficients, rolling friction coefficients, and angles of repose between barley seedling stems, and between barley seedling stems and steel plates. The physical properties of barley seedlings were measured through bending tests and angle of repose tests using a CTM2500 universal testing machine (Jinan Zhongluchang Testing Machine Manufacturing Co., Ltd., with a displacement resolution of 0.01 mm and an accuracy of ± 0.01) and a material property test bench.

Referring to the measurement methods of contact parameters for similar materials and similar crop stems (*Weisong et al., 2023*), the static friction coefficients and rolling friction coefficients between barley seedling stems, and between barley seedling stems and steel plates were determined using the inclined plane method with an inclined plane instrument. The selection of the coefficient of restitution parameters was based on previous studies (*Liao et al., 2020; Weisong et al., 2023*). The range of contact physical parameters of barley seedling stems obtained through experiments is shown in Table 1.

Table 1

Physical parameters for barley seedling stem-contact interface

Parameter	Range	Mean value
Length of barley seedling stems [L/mm]	160~220	180
Diameter of barley seedling stems [L/mm]	1.4~2.2	1.8
Moisture content of barley seedling stems [%]	67.4~79.6	73.4
Coefficient of restitution between barley seedling stems	0.2~0.5	0.35
Static friction coefficient between barley seedling stems	0.5~0.9	0.7
Rolling friction coefficient between barley seedling stems	0.1~0.3	0.2

Parameter	Range	Mean value
Coefficient of restitution between barley seedling stems and steel plates	0.2~0.5	0.35
Static friction coefficient between barley seedling stems and steel plates	0.4~0.8	0.6
Rolling friction coefficient between barley seedling stems and steel plates	0.05~0.2	0.13

Angle of repose

The angle of repose of the stems was tested using the cylinder lifting method (Liao et al., 2020). The average length of barley seedling stems at the harvesting stage is 180 mm. According to the requirements for chopping length in post-harvest processing and ensiling of barley seedlings, the stems of harvested seedlings were preprocessed into 3 types of particle samples with lengths of 20 mm, 30 mm, and 40 mm. For each sample, 100 stems were taken and mixed uniformly in equal proportions. During the experiment, a cylinder (inner diameter 50 mm, height 100 mm) was placed vertically on a horizontal steel plate. The three types of barley seedling stem samples were respectively put into the cylinder, and the cylinder was slowly lifted vertically from the plane at a speed of 0.05 m/s. Under the action of gravity, the barley seedling stems in the cylinder began to fall. After the materials stopped moving, image acquisition was performed. The right contour of the image was intercepted, and the selected image was subjected to binarization and grayscale processing using Matlab2020b software. The contour image of the angle of repose of barley seedling stems was extracted and fitted to obtain the inclination angle of the material contour, as shown in Figure 1. The experiment was repeated 5 times, and the final measured average angle of repose of barley seedling stems was 20.42° , with a coefficient of variation of 1.48%.

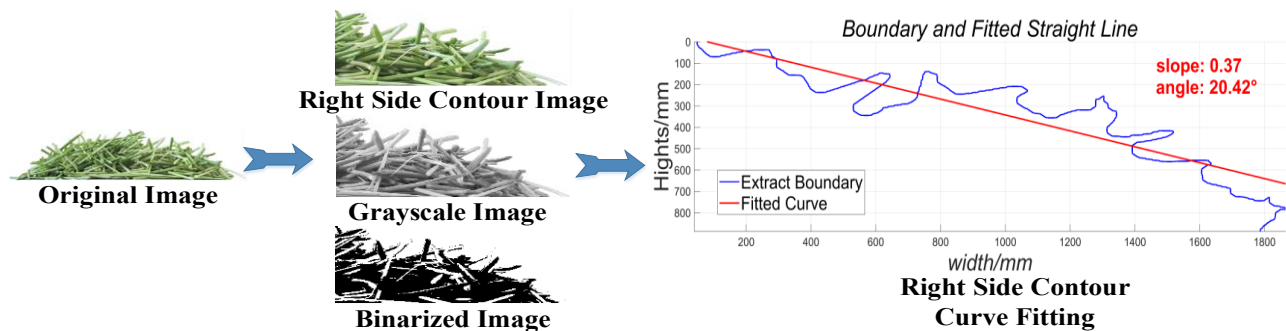


Fig. 1 - Actual repose angle contour extraction

Mechanical Parameters

Since Poisson's ratio has no significant impact on simulation experiments (Du et al., 2025), Poisson's ratio μ_1 is set to 0.33 with reference to similar crop stems (Weisong et al., 2023; Leblcq et al., 2025). Using a CTM2500 universal testing machine, tensile tests were conducted at a loading speed of 5 mm/min to determine the tensile strength and elastic modulus of barley seedling stems. The results showed that the elastic modulus was 10.31 MPa and the shear modulus was 3.87 MPa. Three-point bending tests on barley seedling stems were conducted using a CTM2500 universal testing machine. For the tests, barley seedling stems with a pre-fabricated length of 100 mm were selected. Supported bending was adopted in the bending tests, with a distance of 40 mm between the two fixed supports. A load was applied to the barley seedling stems using an indenter at a speed of 5 mm/min, and the test was repeated 5 times. The maximum loads from the five tests were 2.41 N, 2.52 N, 2.63 N, 2.73 N, and 2.81 N, respectively, resulting in an average maximum load of 2.62 N. This value was used as the target value for the calibration of simulation tests on flexible barley seedling straws in the paper.

Establishment and simulation method of barley seedling stem simulation model

Establishment of rigid model and simulation parameter settings for barley seedlings

The Hertz—Mindlin (no slip) model in EDEM software was used to conduct stacking simulation tests on barley seedling stems. The core of this model is to, through a simplified physical model and within computationally feasible limits, convert the complex process of stem stacking— involving numerous nonlinear contacts, friction, and the synergistic effect of gravity—into a time-stepping mechanical equilibrium problem between particles. Finally, by statistically analyzing the steady-state results of particle movement, the macroscopic characteristic parameter of the angle of repose is obtained.

In essence, it uses classical mechanics theory as a bridge connecting microscopic particle behavior and macroscopic physical phenomena, realizing the mechanism modeling and numerical reproduction of the stem stacking process.

Barley seedling stems are approximately cylindrical. Using the method of combining spherical particles (Guo *et al.*, 2024; Chen *et al.*, 2024) and consistent with the requirements of the physical test for the angle of repose of barley seedling stems, rigid models of barley seedling stems with three different lengths (as shown in Figure 2) were established. To simplify the model, the diameter of the stem particles is 1.6 mm.

Each simulation parameter in the test was selected according to Table 1. Among them, the Poisson's ratio, shear modulus, and density of the steel plate were taken as 0.3, 3.87×10^6 Pa, and 7800 kg/m^3 respectively, based on previous studies (Liao *et al.*, 2020; Weisong *et al.*, 2023).

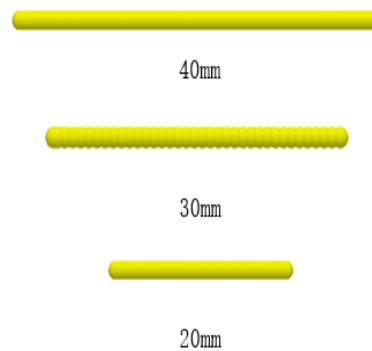


Fig. 2 - Rigid model of barley seedling stems

In EDEM software, a virtual cylinder consistent with the test cylinder was established as a particle factory using the Cylinder model in Geometries, with an inner diameter of 50 mm and a height of 100 mm. The particle factory adopted a dynamic generation method to generate 150 barley seedling stems of each of the three aforementioned different lengths, totaling 450 stems. After the generated stems were static and stable, the cylinder was lifted upward at a speed of 0.1 m/s. The simulation time was 4 s, and the time step was 25%. The results of the EDEM simulation test are shown in Figure 3.



Fig. 3 - Simulation experiment of angle of repose for barley seedling stems

Establishment of Flexible Model for Barley Seedling Stems

According to the real morphology of barley seedling stems, a hollow flexible model of barley seedling stems was constructed using the small particle bonding method. The construction process is as follows: in EDEM, a small particle model with a diameter of 1 mm and a cylindrical model with a diameter of 18 mm, a length of 180 mm and symmetric about the origin center were established, and then the cylinder was filled with the constructed small particles; and through the Hertz-Mindlin with bonding model in EDEM, bonding was generated between particles, and the finally generated stem model view is shown in Figure 4.

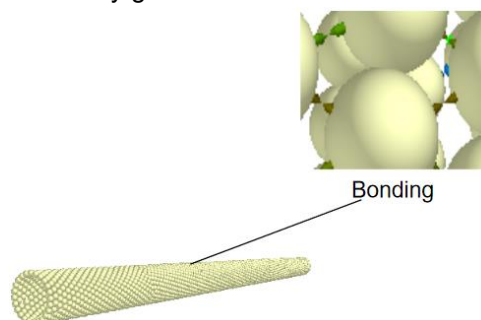


Fig. 4 - Flexible model of barley seedling stem

Simulation Parameter Settings

A cutter model was established using the 3D software SolidWorks as shown in Figure 5. Two supporting seats were set with the cutter as the center, and the distance between the two supporting seats was 60 mm. The model was imported into EDEM through the Geometries command in EDEM software. In the post-processing interface, the set simulation model was exported through Simulation Deck, and the start time was set to 0 s for the convenience of subsequent simulation settings. The cutter movement speed was set to 0.005 m/s in the vertically downward direction, with a time step of 2×10^{-7} s and a data saving interval of 0.001 s.

The basic contact parameters of the simulation model adopted the determined parameters of the Hertz-Mindlin model. The value ranges of bonding parameters such as normal contact stiffness, tangential contact stiffness, critical normal stress, critical tangential stress, and bonding radius were obtained through pre-experiments and references (Liao et al., 2020; Weisong et al., 2023) as follows: $1 \times 10^{10} \sim 4 \times 10^{10}$, $3 \times 10^9 \sim 9 \times 10^9$, $1 \times 10^8 \sim 9 \times 10^8$, $1 \times 10^8 \sim 9 \times 10^8$, and 0.05~0.2 respectively.

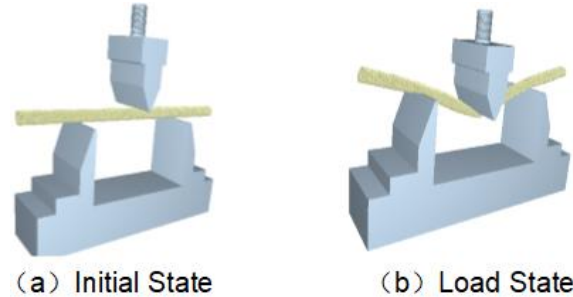


Fig. 5 - Bending simulation of flexible model of barley seedling stem

Contact Parameter Calibration

Plackett-Burman Test

The contact parameters that can affect the simulated physical properties of barley seedling stems, including the coefficient of restitution (x_1) between barley seedling stems, static friction coefficient (x_2), rolling friction coefficient (x_3), as well as the coefficient of restitution (x_4) between barley seedling stems and the steel plate, static friction coefficient (x_5), and rolling friction coefficient (x_6), were taken as test factors, with the angle of repose as the evaluation index. A simulated Plackett-Burman test was conducted to screen out the parameters that have a significant influence on the angle of repose of barley seedlings. The range of values for the test factors was determined based on the measured values from physical tests, as shown in Table 2. A Plackett-Burman design with $N=11$ was adopted, and the test design and simulation results are shown in Table 3. The influence effects of each parameter obtained from the analysis of variance are shown in Table 4.

Table 2

Factor coding for Plackett-Burman test of physical parameters

Factor	coding	
	-1	1
Coefficient of restitution between barley seedling stems x_1	0.2	0.5
Static friction coefficient between barley seedling stems x_2	0.5	0.9
Rolling friction coefficient between barley seedling stems x_3	0.05	0.3
Coefficient of restitution between barley seedling stems and steel plate x_4	0.2	0.5
Static friction coefficient between barley seedling stems and steel plate x_5	0.4	0.8
Rolling friction coefficient between barley seedling stems and steel plate x_6	0.1	0.3

Table 3

Two-level factor experiment design and results

Serial number	Factor						Angle of repose $\theta_1 / (^\circ)$
	x_1	x_2	x_3	x_4	x_5	x_6	
1	0.5	0.9	0.05	0.5	0.8	0.3	24.12
2	0.2	0.9	0.3	0.2	0.8	0.3	26.52
3	0.5	0.5	0.3	0.5	0.4	0.3	19.92

Serial number	Factor						Angle of repose $\theta_1 / (^\circ)$
	X_1	X_2	X_3	X_4	X_5	X_6	
4	0.2	0.9	0.05	0.5	0.8	0.1	23.14
5	0.2	0.5	0.3	0.2	0.8	0.3	22.58
6	0.2	0.5	0.05	0.5	0.4	0.3	18.21
7	0.5	0.5	0.05	0.2	0.8	0.1	18.16
8	0.5	0.9	0.05	0.2	0.4	0.3	19.59
9	0.5	0.9	0.3	0.2	0.4	0.1	23.56
10	0.2	0.9	0.3	0.5	0.4	0.1	22.59
11	0.5	0.5	0.3	0.5	0.8	0.1	19.08
12	0.2	0.5	0.05	0.2	0.4	0.1	18.13

Table 4

Significance analysis of parameters in Plackett-Burman test

Parameter	Effect	Mean Sum of Squares	Influence rate / %	Significance ranking
X_1	-1.13	3.79	2.34	4
X_2	3.91	45.79	28.3	1
X_3	2.15	13.87	8.57	2
X_4	-0.25	0.19	0.1128	6
X_5	1.94	11.21	6.93	3
X_6	1.05	3.29	2.03	5

As can be seen from Table 4, the significance of factors is ranked according to the influence rate. In the test on the angle of repose of barley seedling stems, x_2 , x_3 , and x_5 have a significant influence on the angle of repose of barley seedling stems, while the other factors have no significant influence. Therefore, only these three significant parameters need to be considered in the steepest ascent test and response surface test, and the remaining non-significant parameters take the middle level, i.e., $x_1=0.35$, $x_4=0.35$, $x_6=0.2$.

Steepest ascent Test

Since x_2 , x_3 , and x_5 all have positive effects on the angle of repose, that is, the angle of repose of barley seedling stems increases with the increase of these parameters, and their influences on the angle of repose of barley seedling stems are significant. Therefore, a steepest ascent test was conducted to quickly determine the optimal parameter range, and the values of the angle of repose and the relative errors occurring in the test were recorded. The test design and results are shown in Table 5. It can be seen from Table 5 that as the significant parameters (i.e., the static friction coefficient between barley seedling stems, the rolling friction coefficient between barley seedling stems, and the static friction coefficient between barley seedling stems and the steel plate) increase, the relative error between the simulated angle of repose and the physical angle of repose shows a trend of first decreasing and then increasing. Among them, the relative error is the smallest (6.93%) in the 2nd group of data; thus, the parameters of the 2nd group are selected as the optimal parameters. The adjacent 1st and 3rd groups of data are taken as the high-level and low-level simulation test data, respectively, for the subsequent Box-Behnken test design.

Table 5

Steepest ascent experiment design and results

Serial number	X_2	X_3	X_5	Angle of repose $\theta_1 / (^\circ)$	Relative error $\delta / \%$
1	0.58	0.1	0.48	18.34	10.41
2	0.64	0.15	0.56	21.89	6.93
3	0.72	0.2	0.64	23.86	16.56
4	0.8	0.25	0.72	28.32	38.34
5	0.88	0.3	0.8	34.93	70.64

Box-Behnken

Based on the results screened out from the steepest ascent test, a three-factor and three-level response surface experimental design was conducted for the three basic contact parameters x_2 , x_3 , and x_5 using Design-Expert 13. The central level was set with 5 replicates, and a total of 17 simulation tests were carried out. The experimental coding is shown in Table 6, and the simulation results are shown in Table 7.

Table 6

Box-Behnken test factor encoding

Factor	Coding		
	-1	0	1
x_2	0.58	0.65	0.72
x_3	0.1	0.15	0.2
x_5	0.48	0.56	0.64

Table 7

Box Behnken experimental design scheme and results

Serial number	x_2	x_3	x_5	Angle of repose $\theta_1/(\circ)$	Relative error $\delta/\%$
1	0.58	0.1	0.56	18.75	8.17
2	0.72	0.1	0.56	20.25	0.83
3	0.58	0.2	0.56	19.51	4.46
4	0.72	0.2	0.56	22.82	11.75
5	0.58	0.15	0.48	18.91	7.39
6	0.72	0.15	0.48	20.15	1.32
7	0.58	0.15	0.64	19.50	4.51
8	0.72	0.15	0.64	22.95	12.39
9	0.65	0.1	0.48	19.21	5.93
10	0.65	0.2	0.48	20.65	1.13
11	0.65	0.1	0.64	21.62	5.88
12	0.65	0.2	0.64	22.80	11.66
13	0.65	0.15	0.56	21.75	6.51
14	0.65	0.15	0.56	20.91	2.40
15	0.65	0.15	0.56	22.33	9.35
16	0.65	0.15	0.56	22.11	8.27
17	0.65	0.15	0.56	21.61	5.82

Table 8

Analysis of variance (ANOVA) for physical parameters in Box-Behnken design

Source of Variance	Sum of Squares	Degrees of freedom	Mean Square	F	P
model	31.69	9	31.69	17.27	0.0005**
x_2	11.28	1	11.28	55.35	0.0001**
x_3	4.43	1	4.43	21.71	0.0023**
x_5	7.90	1	7.90	38.76	0.0004**
x_2x_3	0.82	1	0.82	4.02	0.0850
x_2x_5	1.22	1	1.22	5.99	0.0443*
x_3x_5	0.02	1	0.02	0.08	0.7817
x_2^2	4.65	1	4.65	22.82	0.0020**
x_3^2	0.54	1	0.54	2.65	0.1473

Source of Variance	Sum of Squares	Degrees of freedom	Mean Square	F	P
x_5^2	0.41	1	0.41	2.03	0.1972
residual	1.43	7	0.2038		
lack of fit	0.2359	3	0.0786	0.2641	0.8486
pure error	1.19	4	0.2977		

DesignExpert 13.0 software was used to conduct variance analysis on the results of the Box-Behnken test for physical parameters, and the analysis results are shown in Table 8. It can be seen from Table 8 that x_2 , x_3 , x_5 , and x_2x_5 have significant effects on barley seedling stems, while x_2x_3 and x_3x_5 have no significant effects on the angle of repose. The fitted regression model for this angle of repose is significant ($P=0.0005$), and the lack of fit term is not significant ($P=0.8486$). It can be concluded that the model has a good fitting degree with no lack of fit phenomenon. The coefficient of determination and adjusted coefficient of determination are very close to 1, and the coefficient of variation is 2.16%, which proves that this model can reflect the real situation and can be used to predict the angle of repose of barley seedling stems. After removing the non-significant factors, the quadratic regression equation of the simulated angle of repose of barley seedling stems with the three significant parameters is as follows:

$$\theta_0 = -60.53 + 221.16x_2 - 17.04x_3 + 5.59x_5 + 98.66x_2x_5 - 214.48x_2^2 \quad (1)$$

Based on the results of the Box-Behnken test and the regression equation, with the average value of the angle of repose of barley seedling stems obtained from physical tests (20.42°) as the target value, the Numerical module of Design-Expert software was used to conduct an optimal solution analysis on factors x_2 , x_3 , and x_5 . Constraint optimization conditions were set with reference to the results of physical tests, and the constructed nonlinear programming parameter model is as follows:

$$\begin{cases} 0.58 \leq x_2 \leq 0.72 \\ 0.1 \leq x_3 \leq 0.2 \\ 0.48 \leq x_5 \leq 0.64 \end{cases} \quad (2)$$

Through optimization solving, it is found that when the parameter combination of x_2 , x_3 , and x_5 is 0.63, 0.12, and 0.53, the simulated value of the angle of repose of barley seedling stems reaches the optimal. Under these parameters, 5 repeated tests were conducted via discrete element simulation, and the average value of the angle of repose was 20.58° . The relative error with the average value of the angle of repose from physical tests is 0.78%, indicating that the established predictive regression model for the angle of repose of barley seedling stems is relatively accurate.

Verification of Simulation Test for Angle of Repose

Under the same conditions as the above tests, 5 repeated verification tests were conducted based on the optimization results. After comprehensively considering the actual test situation and rounding the optimized parameters, specifically, the static friction coefficient and dynamic friction coefficient between barley seedling stems were set as 0.6 and 0.1 respectively, and the static friction coefficient between barley seedling stems and the steel plate was set as 0.5. Non-significant parameters were set as the median values within the range measured by physical tests for test verification. The relative error between the average angle of repose of barley seedlings in the verification test and the theoretical optimization result was 0.54%, indicating that the regression model has good reliability and the calibrated physical parameters for the contact of barley seedling stems are feasible.

Calibration of Bond Parameters

Plackett-Burman Test

The bonding parameters that affect the simulated mechanical properties of barley seedlings, including the normal contact stiffness (x_7), tangential contact stiffness (x_8), critical normal stress (x_9), critical tangential stress (x_{10}), and bonding radius (x_{11}) of barley seedling stems, were taken as experimental factors, and the bending stress was used as the evaluation index to conduct a simulated Plackett-Burman test, aiming to screen out the parameters that have significant effects on the bending stress of barley seedlings. For the simulated Plackett-Burman test, references were made to similar stem crops such as tea stems (*Du et al., 2025*) for determining the ranges of the normal contact stiffness (x_7), tangential contact stiffness (x_8), critical normal

stress (x_9), and critical tangential stress (x_{10}) of barley seedling stems, and the bonding radius (x_{11}) was set as shown in Table 9. A Plackett-Burman design with $N=11$ was adopted. The experimental design and simulation results are presented in Table 10, and the influence effects of each parameter obtained from the variance analysis are shown in Table 11.

Table 9

Value ranges of bonding parameters in Plackett-Burman design

factor	coding	
	-1	1
Normal contact stiffness $x_7/(N \cdot m^{-1})$	1×10^{10}	4×10^{10}
Tangential contact stiffness $x_8/(N \cdot m^{-1})$	3×10^9	9×10^9
Critical normal stress x_9/Pa	1×10^8	9×10^8
Critical tangential stress x_{10}/Pa	1×10^8	9×10^8
Bond radius x_{11}/mm	0.28	0.42

Table 10

Plackett-Burman experimental design and results for bonding parameters

Serial number	$x_7 / (N \cdot m^{-1})$	$x_8 / (N \cdot m^{-1})$	x_9 / Pa	x_{10} / Pa	x_{11} / mm	Bending stress F/N
1	4×10^{10}	9×10^9	1×10^8	9×10^8	0.42	1.03
2	1×10^{10}	9×10^9	9×10^8	1×10^8	0.42	4.61
3	4×10^{10}	3×10^9	9×10^8	9×10^8	0.28	1.32
4	1×10^{10}	9×10^9	1×10^8	9×10^8	0.42	2.01
5	1×10^{10}	3×10^9	9×10^8	1×10^8	0.42	2.71
6	1×10^{10}	3×10^9	1×10^8	9×10^8	0.28	1.41
7	4×10^{10}	3×10^9	1×10^8	1×10^8	0.42	3.22
8	4×10^{10}	9×10^9	1×10^8	1×10^8	0.28	4.08
9	4×10^{10}	9×10^9	9×10^8	1×10^8	0.28	2.20
10	1×10^{10}	9×10^9	9×10^8	9×10^8	0.28	2.43
11	4×10^{10}	3×10^9	9×10^8	9×10^8	0.42	3.25

Table 11

Significance test results of Plackett-Burman design for adhesion parameters

Source of Variance	Sum of Squares	degrees of freedom	Mean Square	F	P
model	13.96	5	2.79	11.48	0.0050**
x_7	3.89	1	3.89	16.00	0.0071**
x_8	2.08	1	2.08	8.54	0.0266*
x_9	0.008	1	0.008	0.033	0.8619
x_{10}	1.04	1	1.04	4.27	0.0842
x_{11}	6.95	1	6.95	28.58	0.0018**
residual	1.46	6	0.243		
total	15.41	11			

It can be seen from Table 10 that among the factors affecting the bending stress of barley seedling stems, x_7 , x_8 , and x_{11} have significant effects on the bending stress of barley seedling stems, while other factors have no significant effects. Therefore, only these three significant parameters need to be considered in the steepest ascent test and response surface test, and the remaining non-significant parameters are set at the mid-level, i.e., x_9 is 5×10^8 and x_{10} is 5×10^8 .

Steepest ascent Test

It can be seen from Table 12 that as each significant parameter (normal contact stiffness, tangential contact stiffness, and bonding radius) increases, the relative error between the simulated bending stress and the actual bending stress first decreases and then increases. Among them, the relative error in the 3rd group of data is the smallest at 3.05%, so the 3rd group of parameters is selected as the optimal choice. The adjacent 2nd and 4th groups of data are taken as the high-level and low-level simulation test data respectively for the subsequent Box-Behnken test design.

Table 12

Design and results of the steepest climbing test for bonding parameters

Serial number	$x_7 / (\text{N} \cdot \text{m}^{-1})$	$x_8 / (\text{N} \cdot \text{m}^{-1})$	x_{11} / mm	Bending stress F_t / N	Relative error $\delta / \%$
1	1.6×10^{10}	4.2×10^9	0.29	1.08	58.77
2	2.2×10^{10}	5.4×10^9	0.33	1.89	27.86
3	2.8×10^{10}	6.6×10^9	0.36	2.54	3.05
4	3.4×10^{10}	7.8×10^9	0.39	3.06	16.79
5	4×10^{10}	9×10^9	0.42	3.82	45.8

Box-Behnken

Using DesignExpert 13.0 software, with the value of No. 3 in the steepest ascent test as the center point, and the values of No. 2 and No. 4 as the low level and high level respectively, a three-factor and three-level Box-Behnken experimental design was conducted, with 17 sets of simulation tests carried out in the design. The test codes are shown in Table 13, and the test results are shown in Table 14.

Table 13

Box-Behnken test factor encoding

factor	coding		
	-1	0	1
x_7	2.2×10^{10}	2.8×10^{10}	3.4×10^{10}
x_8	5.4×10^9	6.6×10^9	7.8×10^9
x_{11}	0.33	0.36	0.39

Table 14

Box-Behnken experimental design and results for bonding parameters

Serial number	$x_7 / (\text{N} \cdot \text{m}^{-1})$	$x_8 / (\text{N} \cdot \text{m}^{-1})$	x_{11} / mm	bending stress F_t / N	relative error $\delta / \%$
1	2.2×10^{10}	6.6×10^9	0.33	2.46	6.11
2	2.2×10^{10}	6.6×10^9	0.39	2.75	4.96
3	3.4×10^{10}	6.6×10^9	0.33	2.70	3.05
4	3.4×10^{10}	6.6×10^9	0.39	2.86	9.16
5	2.8×10^{10}	5.4×10^9	0.33	2.41	8.02
6	2.8×10^{10}	5.4×10^9	0.39	2.57	1.91
7	2.8×10^{10}	7.8×10^9	0.33	2.52	3.82
8	2.8×10^{10}	7.8×10^9	0.39	2.85	8.78
9	2.2×10^{10}	5.4×10^9	0.36	2.50	4.58
10	3.4×10^{10}	5.4×10^9	0.36	2.52	3.82
11	2.2×10^{10}	7.8×10^9	0.36	2.59	1.15
12	3.4×10^{10}	7.8×10^9	0.36	2.75	4.96
13	2.8×10^{10}	6.6×10^9	0.36	2.60	0.76
14	2.8×10^{10}	6.6×10^9	0.36	2.65	1.15
15	2.8×10^{10}	6.6×10^9	0.36	2.66	1.53
16	2.8×10^{10}	6.6×10^9	0.36	2.59	1.15
17	2.8×10^{10}	6.6×10^9	0.36	2.58	1.53

DesignExpert 13.0 software was used to perform variance analysis on the results of the Box-Behnken test for bonding parameters, and the analysis results are presented in Table 15. It can be seen from the table that the normal contact stiffness x_7 , tangential contact stiffness x_8 , bonding radius x_{11} , and the quadratic term of tangential contact stiffness have extremely significant effects on the bending stress of barley seedling stems, while the other parameters have no significant effects on the bending stress of barley seedlings. The fitted regression model is significant ($P=0.0003$), and the lack of fit term is not significant ($P=0.4435$), which indicates that the model has a good fitting degree with no lack of fit phenomenon. The influence of the interaction of each significant parameter on the bending stress is shown in Figure 8. The coefficient of determination $R^2=0.9630$ and the adjusted coefficient of determination $R_{adj}^2=0.9155$ are very close to 1, and the coefficient of variation is 1.42%, which proves that this model can reflect the real situation and can be used to predict the bending stress of barley seedling stems. After removing the factors that are not significant to the regression model, the quadratic regression equation of the simulated bending stress of barley seedling stems with the four significant parameters is as follows:

$$F_1 = 6.50 - 1.75 \times 10^{-11} x_7 + 1.13 \times 10^{-10} x_8 - 28.42 x_{11} - 4.55 \times 10^{-20} x_8^2 \quad (3)$$

Based on the results of the Box-Behnken test and the regression equation, with the average value of the bending stress of barley seedling stems obtained from physical tests (2.62 N) as the target value, the Numerical module of Design-Expert software was used to conduct an optimal solution analysis on factors x_7 , x_8 , and x_{11} . Constraint optimization conditions were set with reference to the actual physical test results, and the constructed nonlinear programming parameter model is as follows:

$$\begin{cases} 2.2 \times 10^{10} \leq x_7 \leq 3.4 \times 10^{10} \\ 5.4 \times 10^{10} \leq x_8 \leq 7.8 \times 10^{10} \\ 0.33 \leq x_{11} \leq 0.39 \end{cases} \quad (4)$$

Through optimization calculation, it is found that when the parameter combination of x_7 , x_8 , and x_{11} is $3.12 \times 10^{10} \text{ N/m}^{-1}$, $6.66 \times 10^9 \text{ N/m}^{-1}$, and 0.35 mm, the simulated value of the bending stress of barley seedling stems reaches the optimal. Under these parameters, 5 repeated tests are conducted via discrete element simulation, and the average value of the bending stress is 2.6 N. The relative error with the average value of the shear destructive force from physical tests is 0.76%, indicating that the established predictive regression model for the bending stress of barley seedling stems is relatively accurate.

Table 15

Analysis of Variance (ANOVA) for Bonding Parameters in Box-Behnken Design

Source of Variance	Sum of Squares	degrees of freedom	Mean Square	F	P
model	0.2538	9	0.0282	20.26	0.0003**
x_7	0.0351	1	0.0351	25.22	0.0015**
x_8	0.0630	1	0.0630	45.26	0.0003**
x_{11}	0.1105	1	0.1105	79.34	< 0.0001 **
$x_7 x_8$	0.0049	1	0.0049	3.52	0.1028
$x_7 x_{11}$	0.0042	1	0.0042	3.03	0.1250
$x_8 x_{11}$	0.0072	1	0.0072	5.19	0.0568
x_7^2	0.0066	1	0.0066	4.72	0.0664
x_8^2	0.0181	1	0.0181	12.98	0.0087**
x_{11}^2	0.0058	1	0.0058	4.14	0.0813
residual	0.0097	7	0.0014		
lack of fit term	0.0044	3	0.0015	1.11	0.4435
pure error	0.0053	4	0.0013		

Three-point bending simulation test verification

Under the same conditions as the aforementioned tests, 5 repeated verification tests were conducted based on the optimization results. After comprehensively considering the actual test situation and rounding the optimized parameters, the normal contact stiffness, tangential contact stiffness, and bonding radius of barley

seedling stems were set as $3.1 \times 10^{10} \text{ N/m}^{-1}$, $6.7 \times 10^9 \text{ N/m}^{-1}$, and 0.35 mm respectively. Non-significant parameters were set as the median values within the range measured by physical tests for test verification. The comparison test and verification curves are shown in Figure 7. The relative error between the average bending stress of barley seedlings in the verification tests and the theoretical optimization result is 0.76%, which indicates that the regression model has good reliability and the calibrated bonding parameters of barley seedling stems are relatively accurate.

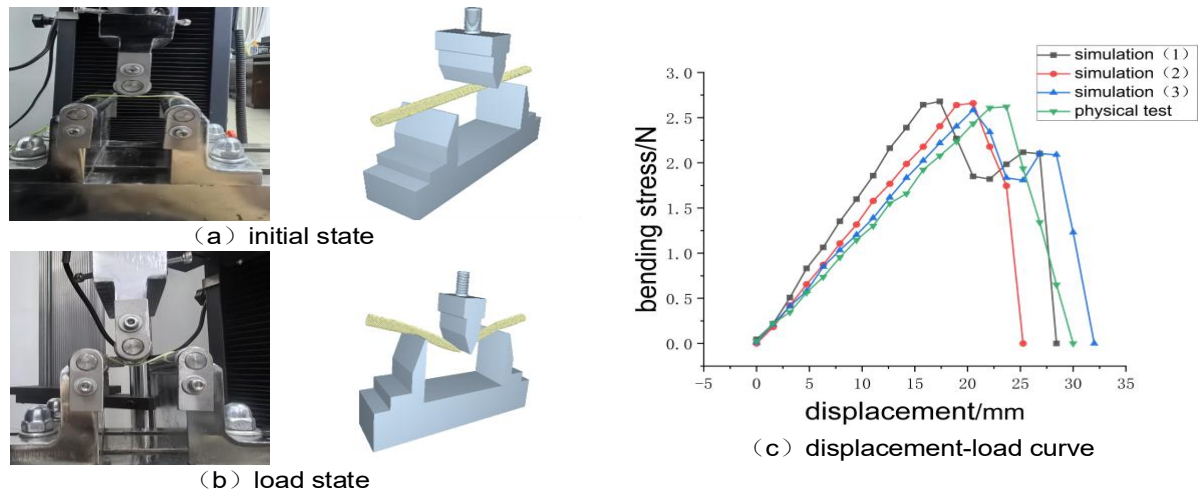


Fig. 6 - Comparison of bending test results between simulation and physical experiments for barley seedling stalks

CONCLUSIONS

(1) Through physical tests, it was measured that the average diameter of barley seedling stems was 1.8 mm, the density was 125 kg/m^3 , and the moisture content was 73.4%. Additionally, the value ranges of physical parameters such as Poisson's ratio, shear modulus, static friction coefficient, rolling friction coefficient, and coefficient of restitution were determined. The test measured that the average angle of repose of barley seedling stems was 20.42° , and the average maximum load of stems in the three-point bending test was 2.62 N.

(2) A rigid model of barley seedling stems was established based on the Hertz-Mindlin (no slip) model. Through Plackett-Burman test, steepest ascent test, and Box-Behnken test, the parameters that significantly affect the angle of repose were screened out, including the stem-stem static friction coefficient, rolling friction coefficient, coefficient of restitution, as well as the stem-steel plate static friction coefficient, rolling friction coefficient, and coefficient of restitution. The optimized parameter combinations are 0.63, 0.12, 0.35, 0.53, 0.2, and 0.35, respectively. The relative error between the simulation result of the angle of repose and the physical test result is 0.54%, indicating that the calibrated physical parameters are accurate, and the established rigid model can reflect the physical properties of barley seedling stems, which can provide a reference for the design of barley seedling harvesters.

(3) Based on the Hertz-Mindlin with bonding model, a flexible model of barley seedling stems was established. Through tests, the bonding parameters that significantly affect the bending stress were screened out, including normal contact stiffness, tangential contact stiffness, and bonding radius. The optimal parameter combination obtained through optimization is as follows: the normal contact stiffness is $3.12 \times 10^{10} \text{ N/m}^{-1}$, the tangential contact stiffness is $6.66 \times 10^9 \text{ N/m}^{-1}$ and the bonding radius is 0.35 mm. In the three-point bending simulation test, the relative error between the simulated bending stress and the physical test is 0.76%, indicating that the calibrated bonding parameters are reliable, and the established flexible model can reflect the mechanical properties of barley seedling stems, which can provide a theoretical basis for the design and optimization of the cutting mechanism of barley seedling harvesting machinery.

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