MAIZE STRAW CUTTING PROCESS MODELLING AND PARAMETER CALIBRATION BASED ON DISCRETE ELEMENT METHOD (DEM)
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基于离散元法的玉米秸秆切断模型构建及参数标定

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ABSTRACT
In order to simulate straw cutting process, this paper established a maize straw cutting model with discrete element method (DEM) based on straw cutting experiment. Firstly, maize straw model consisting of several small particles was established by DEM. Then, a straw cutting experiment was conducted and the maximum straw cutting resistance was 199 N for straw with 15 mm diameter. Then, single-factor experiment was conducted to analyze the effect of DEM parameters on straw cutting effect and the max straw cutting resistance F_{max}*. The normal stiffness between particles and blade (ball-facet-kn) and shear stiffness between particles and blade (ball-facet-ks) were found to be the significant factors affecting* F_{max}*, and the value of the parameters that has no significance was determined. The optimum combination of the significant parameters was 17662* $N \cdot m^{-1}$ *of ball-facet-kn and 52499* $N \cdot m^{-1}$ *of ball-facet-ks. The verification test results showed that the maize straw model was cut off, thus it could simulate the real straw cutting effect, and the relative error of max straw cutting resistance* F_{max} *between the simulation and the experiment was below 9.1%. Thus, it could be concluded that the established maize straw cutting model was accurate and reliable.*

摘要
玉米秸秆切断是秸秆粉碎还田、少免耕播种等作业中重要的技术环节之一，对玉米秸秆进行离散元建模及参数标定，有利于更好地理解分析玉米秸秆切断行为。本文首先利用万能材料试验机进行秸秆切断试验，测得秸秆最大切断力。其次通过单因素试验，分析不同离散元模型参数对玉米秸秆切断效果及最大切断力的影响，筛选出对玉米秸秆模型最大切断力有显著影响的参数为颗粒墙体间法向刚度 ball-facet-kn 与切向刚度 ball-facet-ks，并确定了其他非显著因素的值。通过最陡爬坡试验确定了这两个关键参数的最优区间，在此基础上，根据中心旋转组合试验建立了最大切断力与显著性参数的二阶线性回归模型。通过 Design-Expert 优化模块，以最大切断力为目标，得出显著性参数的最佳组合为：颗粒墙体间法向刚度和切向刚度分别为17662 和52499 $N \cdot m^{-1}$*。最优参数组合验证试验表明，秸秆模型和秸秆颗粒之间粘结键被从中间切断，所校核参数模型可模拟真实切断效果，且不同直径秸秆最大切断力仿真值与试验值误差不超过 9.1%，所建立秸秆模型准确可靠。研究结果可为少免耕播种、秸秆还田中玉米秸秆切断过程研究提供参考。*

INTRODUCTION
Straw returning is a technology that returns the post-harvest straw into field directly or indirectly. Straw returning could improve soil structure, enhance soil fertility, reduce straw burning, etc. (*Wang et al., 2017; Liu et al., 2019; Gao et al., 2004; Yu et al., 2014*). In straw returning, the straw touching parts of the straw smashing or no/minimum till seeding machinery, such as rotary blades and smashing blades interact with straw, so as to cut them off into small pieces (*Zhang et al., 2018*). Therefore, it is necessary to investigate the straw cutting process to improve straw returning quality.

The traditional straw cutting experiment is restricted by farming season and high economic cost. The discrete element method (DEM), a computer simulation technology which is used to analyze the dynamic characteristics of the target through discrete particles, has been more and more popular in agricultural machinery research. It is fast, economic and convenient to record minor behaviour of agricultural materials (*Shmulevich, 2010*).

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Modelling the straw cutting process by DEM could help to understand the straw cutting behavior and provide theory basis for the development of straw returning machine and no/minimum till seeders.

A set of research were conducted on the DEM modelling of crop straw, *Zhang et al. (2018)* and *Huo et al. (2011)* calibrated repose angle and restitution coefficient of straw model; *Bart Lenaerts et al. (2016), Leblicq et al. (2014)* and *Liu et al. (2018)* established bendable straw model with flexibility to simulate the straw deformation process. *Liao et al. (2020)* simulated the chopping process of fodder rape crop straw in bolting stage. *Zhang et al. (2019)* modelled the straw kneading and crushing process. However, seldom research was done on the maize straw cutting process and the calibration of relevant parameters.

Therefore, this paper intended to establish a straw cutting model based on DEM, and simulate the straw cutting process, analyze the key parameters' effect on straw cutting effect and straw cutting force, and calibrate the DEM parameters.

MATERIALS AND METHODS

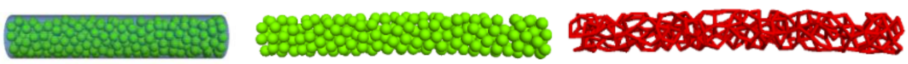
Basic parameters of the maize straw

The straw sample (Fig.1) was taken right after maize harvesting from an experiment station of China Agricultural University located at Zhuozhou city, Hebei province (115°56′E, 39°28′N), the maize variety Huaiyu 20 was commonly planted around Zhuozhou city. The average water content of the straw sample was 17.2%, and the average diameter was 15mm.

Fig. 1 - Straw samples to be tested

Establishment of the straw DEM model

The straw model was established with the DEM software PFC^{3D}5.0 (*Itasca, 2017*). In PFC^{3D}5.0, there were two major elements: balls and walls. Agricultural materials can be modeled by balls or ball agglomerates, agricultural machinery or its components can be modeled by combination of walls. Considering the complexity of straw physical composition, it is difficult to establish model in real structure. According to the previous literature, the DEM straw model was established in isotropy with small particles. The contact model between straw particles adopted the parallel bond model, which could bond the adjacent particles together when their distance is in a limited range. And only if the stress exceeds the default value, the bond breaks and particles separate, which could simulate the straw cutting behaviour. Firstly, a cylinder wall with 15mm diameter and 120mm length was established, then the cylinder wall was filled up with particles having 1.8mm diameter. After the initial unbalance force of the particles dissipated, the cylinder wall was deleted and cohesion was endowed between particles to bond together, then the straw model was established as shown in Fig.2.



a) *b)* *(c)*

Fig.2 - Establishment of DEM cutting straw model

a) generation of particles in the cylinder to model the straw; b) straw model with cohesion; c) the parallel bond between particles

Experiment methods

Firstly, the universal material test machine was used to conduct the straw cutting experiment, in order to observe the straw cutting process and determine the straw cutting force. Secondly, single factor simulation experiment was conducted to screen out the DEM parameters preliminarily, calibrate the parameters with no significance and find the parameters that have significant influence on straw cutting forces and effect (*Mak et al., 2012*), then the steepest ascent test was conducted to find out the appropriate range for the significant parameters (*Yuan et al., 2018; Liu et al., 2016*). After that, regression model between max straw cutting force and the significant parameters was confirmed by a Box-Behnken test. At last, the best fit value of the key parameters was archived by finding out the optimum outcome of the regression model. Then, a comparison experiment was carried out to compare the max straw cutting force and straw cutting effect between the simulation and physical experiment, to verify the accuracy of the calibrated parameters' values.

Basic parameters of the DEM straw model

As listed in Table 1, 12 parameters are concluded in this parallel bond DEM model. The friction coefficient between straw and wall, straw density, normal and shear damping coefficient index, bond radius were taken from previous literatures (*Fang et al., 2016; Lu et al., 2016; Li et al., 2016*). Through preliminary experiment, it was found that the other 8 parameters may influence straw cutting force and straw cutting effect, so single factor experiment was done and their values are presumed at a large range.

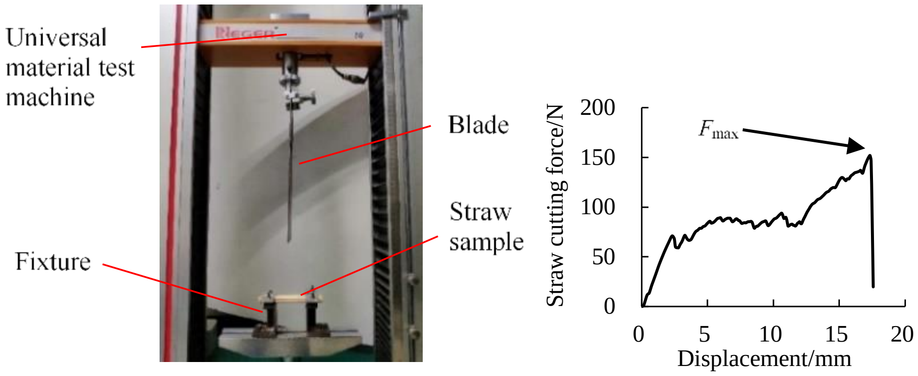
Table 1

Key parameters of maize straw model

Parameters	Value
Density /(kg/m^3)	243
Shear stiffness of the particle ball-ball-kn/ (N·m^{-1})	5~5e5
Normal stiffness of the particle ball-ball-ks/ (N·m^{-1})	5~5e5
Friction coefficient between straw and wall μ	0.35
Shear critical damping coefficient βn	0.5
Normal critical damping coefficient Bs	1
Tensile strength of the bond pb_ten / Pa	5e2~5e6
Cohesion strength of the bond pb_coh/ Pa	1e3~1e7
Normal stiffness of the bond pb_kn/ (N·m^{-1})	2e5~2e9
Shear stiffness of the bond pb_ks/ (N·m-1)	2e5~2e9
Shear stiffness between particle and wall ball-facet-kn/ (N·m^{-1})	2e2~2e6
Normal stiffness between particle and wall ball-facet-ks/ (N·m^{-1})	1e3~1e7
Bonding radius index	0.5

Straw cutting experiment

The straw cutting experiment was conducted using a universal material testing machine (Fig.3). It is developed by Ruigeer Technology Company in Shenzhen and it is a RGM4005 type digital electronic universal material testing machine. To start the experiment, the straw sample was fixed in the fixture first and loaded on the blade, then the blade moved downward and the straw sample was cut off. The straw cutting force can be obtained in the universal material testing machine. The blade material was normal steel with 3mm thickness and 30° throat angle; it moved 60mm/min. The experiment was replicated 30 times.



a） b)

Fig. 3 - Straw cutting experiment

a) Universal material testing machine; b) Real-time straw cutting force

Observing the straw cutting process, the typical resistance variation of the blade can be drawn as Fig.3. The displacement of the blade when it interacted with straw was 0, with the blade moved downward, the blade resistance increased along to the maximum value, when the straw was cut off. Then the blade resistance decreased dramatically and the universal material testing machine stopped operating. The average maximum straw cutting force was 199N from the 30 times experiment.

Establishment of the straw cutting model to calibrate DEM parameters

In order to mimic the straw cutting process and the blade resistance, a straw cutting model was established as shown in Fig.4.

The blade model was first established in SolidWorks software and then imported into DEM software to generate the DEM blade model, its thickness and angle of throat were kept the same within the experiment. The straw model established in chapter 1.1 was fixed by four walls, certain velocity was given to the walls to fix the straw. Then the blade model moved downward in a velocity of 60mm/min to cut off the straw, during which the straw cutting process could be monitored and the straw cutting force could be recorded.

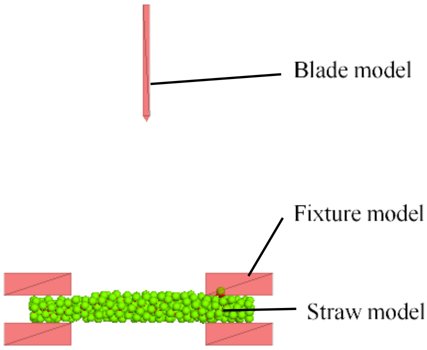


Fig. 4 - DEM simulation of straw cutting

RESULTS AND DISCUSSION

The selection of significant factor by single factor experiment

In order to analyze the effect of the 8 DEM parameters on straw cutting performance and pick out the factors with significant influence, single factor experiment with DEM simulation was conducted. In the simulation experiment, the test factor was changed with different values while the other factors' value was fixed, and the effect on maximum straw cutting force and straw cutting effect of the 8 DEM parameters were examined. The initial factor value of the ball-ball-ks was 500 N·m-1, ball-facet-kn was 2×10^4 $N\cdot m^{-1}$, ball-facet-ks was 1×10^5 $N\cdot m^{-1}$, pb_kn was 2×10^7 N·m-1, pb_ks was 2×10^7 $N\cdot m^{-1}$, pb_ten was 1×10^5 Pa, pb_coh was 5×10^4 Pa. Via the built-in command, random seed can be changed to generate three straw model so that 3-time replicate simulation experiment can be conducted to eliminate experiment error. The effect of these 8 factors on straw cutting force was shown in Fig.5, and the significance analysis was listed in table 2.

Table 2

Significance analysis of different DEM parameters

Simulation factors	F	P value	Significance
Ball-ball-kn	0.12	0.97	
Ball-ball-ks	0.18	0.94	
Ball-facet-kn	23.27	4.7E-05	**
Ball-facet-ks	65.82	3.8E-07	**
Pb_kn	0.17	0.95	
Pb_ks	0.07	0.99	
Pb_ten	0.02	0.99	
Pb_coh	0.02	0.99	

**indicates significant, p<0.05, ** indicates highly significant, p<0.01*

The normal stiffness of the particle ball-ball-kn and shear stiffness of the particle ball-ball-ks represent normal and shear stiffness between the particles which consist in the straw model. During the experiment, the ball-ball-kn value from 5 to 5×10^4 $N\cdot m^{-1}$ was increased while other factors were kept unchanged. Results showed that with the increase of ball-ball-kn, the maximum straw cutting force increased slowly with no significance. It can be observed that the straw cutting effect at 5×10^3 $N\cdot m^{-1}$ was closer to the real experiment than that at 500 $N\cdot m^{-1}$, thus the value of ball-ball-kn was chosen 5×10^3 $N\cdot m^{-1}$. The ball-ball-ks value had no significant influence on maximum straw cutting force either, and had similar influence on straw cutting effect, so its value was chosen 5×10^3 $N\cdot m^{-1}$ with synthesis analysis.

Normal stiffness between particle and wall and shear stiffness between particle and wall represent the contact parameters between blade and straw particles in the straw cutting process, both of which have vital influence on the contact force between blade and straw model. Both of the two parameters had highly significant influence on maximum straw cutting force (p<0.01). With ball-facet-kn increased from 200 to 2×10^6

N·m-1, the maximum straw cutting force displayed an exponential growth from 9N to 16412N, so ball-facet-kn had the greatest influence among the 8 parameters. The maximum straw cutting force was 203N when the ball-facet-kn value was 2×10^{4} N, which was the closest to the target value.

With the increase of ball-facet-ks from 1×10^{3} N·m^{-1} to 1×10^{7}, the maximum straw cutting force increased from 169N to 775N, the maximum straw cutting force reached 203N when ball-facet-ks was 1×10^{5}. These two parameters had the biggest influence on maximum straw cutting force; it is necessary to calibrate them further.

Having the other factors fixed, with the increase of pb_kn, the maximum straw cutting force fluctuated in a small range with no significance. When it was at low value of 2×10^{5} or 2×10^{6} N·m^{-1}, the straw model could not be cut off, and when the value was bigger than 2×10^{8} N·m^{-1}, the straw cutting effect was different from the real situation. With the increase of pb ks, the maximum straw cutting force increased first and then decreased in a small range with no significance. When the pb_ks value was low 2×10^{5} N·m^{-1}, straw could be cut off, but when it was bigger than 2×10^{9} N·m^{-1}, it seemed unreal. By synthesis analysis, the values of the two factors were both set as 2×10^{7} N·m^{-1} which could ensure a straw cutting effect close to the real experiment.

With the other factors fixed, neither pb_ten, nor pb_coh had significant influence on the maximum straw cutting force. It can be observed from the straw cutting process that when the pb_ten value was too low (500 or 5×10^{3} Pa) or when the pb_coh value was too low (1×10^{3} or 1×10^{4} Pa), the straw cutting effect could not be simulated. When the pb_ten was too high, the straw model could not be cut off, but when the pb_coh value was too high, the straw model could still be cut off. By synthesis analysis, the pb_ten and pb_coh were set as 5×10^{4} Pa and 1×10^{5} Pa respectively.

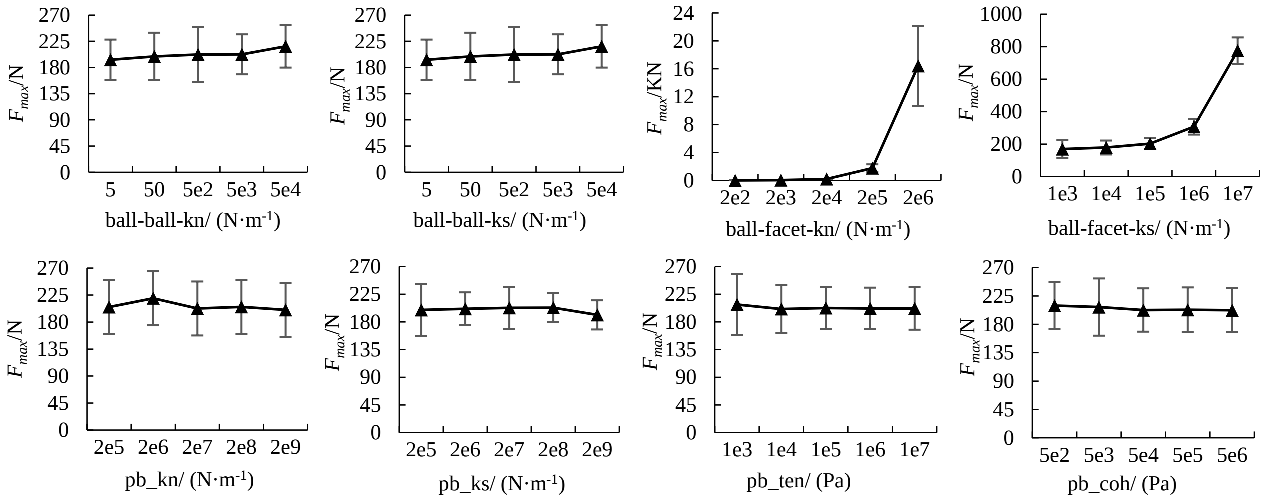


Fig. 5 - Effect of different DEM parameters on the max cutting force

The steepest ascent test to determine the optimum range of the factor value

The steepest ascent test was conducted to determine the optimum range of the significant factors of ball-facet-kn and ball-facet-ks. During the simulation experiment, the value of the two factors was increased step by step, the experiment scheme and results were shown in Table3. With the increase of ball-facet-kn and ball-facet-ks, the maximum straw cutting force increased gradually, the relative error between the simulation value and experiment value of the maximum straw cutting force decreased first and increased after. The smallest relative error of 10.4% occurred in the third simulation experiment, so the optimum range of the factor value was around the third simulation experiment. Therefore, central composite experiment was conducted in the next chapter with the second to fourth experiment factor values, and regression equation would be established to solve the optimum value of these two significant factors.

Table 3

Scheme and results of steepest ascent test

No	ball-facet-kn	ball-facet-ks	F_{max}/N	Relative error /%
1	1e4	5e4	111	79.3
2	1.5e4	7.5e4	167	19.2
3	2e4	1e5	222	10.4
4	2.5e4	1.25e5	278	28.4
5	3e4	1.5e5	327	39.1

Central composite experiment and regression model

Based on the result of the steepest ascent test, central composite experiment was conducted through Design-Expert 8.0 software and the regression model was established. 5 values were set for each factor, and 5 central points were adopted to estimate the error; coding of central composite design factors was shown in Table4. 13-time experiment repetitions were conducted totally.

Table 4

Coding of central composite design factors

Factors	Level				
	1.414	**1**	**0**	**-1**	**-1.414**
Ball-facet-kn	27071	25000	20000	15000	12929
Ball-facet-ks	135355	125000	100000	75000	64645

The experiment scheme and results were shown in Table 5. Design-Expert 8.0 software was used to do the variance analysis (Table 6). It can be seen that both ball-facet-kn and ball-facet-ks had highly significant influence on the maximum straw cutting force ($P < 0.01$), and the linear regression model was also highly significant. So the experiments were reasonable and effective, with all relative significant factors considered. After eliminating the factors with no significance, a well matching regression equation with practical analysis meaning can be drawn. In the regression equation, R represents the maximum straw cutting force, A and B represents ball-facet-kn and ball-facet-ks respectively. The final regression equation after being optimized was

$$R = 188.5652174 + 45.2006403 \times A + 7.424621202 \times B - 6 \times A \times B + 4.456521739 \times A^2 - 6.924621202 \times A^2 \times B$$

Through the optimization module of Design-Expert 8.0 software, the maximum straw cutting force Fmax was set as the target (199N), the optimized regression equation was put into the optimization module of Design-Expert, the best combination value of ball-facet-kn and ball-facet-ks was 17662 $N \cdot m^{-1}$ and 52499 $N \cdot m^{-1}$, respectively.

Table 5

Scheme and results of central composite design

No.	Ball-facet-kn	Ball-facet-ks	F_{max}
1	-1	1	176
2	0	0	189
3	-1.414	0	133
4	-1	-1	189
5	0	0	245
6	0	0	155
7	1	-1	260
8	0	-1.414	197
9	0	1.414	234
10	0	0	189
11	1	1	189
12	1.414	0	142
13	0	0	189

Table 6

ANOVA of central composite design quadratic model

Source	Freedom	mean sum of square	P value
Model		16851	< 0.0001
Ball-facet-kn	1	16345	< 0.0001
Ball-facet--ks	1	221	< 0.0001
AB	1	144	< 0.0001
A^2	1	141	0.0001/
B^2	1	-	-
A^2B	1	96	0.0003

The verification results

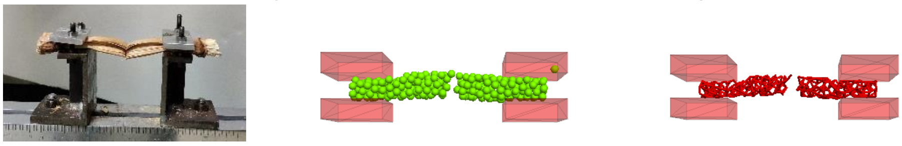
Aiming to verify the accuracy of the value of the two significant factors and other factors determined with the single factor experiment, a verification experiment was conducted. Three straw models with diameter of 13, 15 and 17mm were established and straw cutting process was simulated to compare with the real experiment. The final parameters' values of the DEM model were listed in Table 7.

Table 7

Final parameters of DEM maize straw model

Parameters	Value
ball-ball-kn/ ($N \cdot m^{-1}$)	5×10^3
ball-ball-ks/ ($N \cdot m^{-1}$)	5×10^3
pb_ten / Pa	5×10^4
pb_coh/ Pa	1×10^5
pb_kn/ ($N \cdot m^{-1}$)	2×10^7
pb_ks/ ($N \cdot m^{-1}$)	2×10^7
ball-facet-kn/ ($N \cdot m^{-1}$)	17662
ball-facet-ks/ ($N \cdot m^{-1}$)	52499

The cutting process of the real straw, the DEM straw model and the bond between straw particles were shown in Fig.6. The straw cutting process showed great resemblance between the simulation and the real experiment. The maximum straw cutting forces of the simulation and the experiment were shown in Table 8.



a) b) c)

Fig.6 - Comparison on the straw cutting effect of experiment and simulation

a) Real straw cutting process b) Simulation of straw cutting process c) Simulation of bond cutting process

The relative error of the maximum straw cutting force with different diameters between the simulation and the experiment was below 9.1%, and the maximum straw cutting force showed good linear relation with straw diameter, indicating the accuracy and reliability of the established DEM straw cutting model.

Table 8

Blade resistance in straw cutting simulation

Parameters	Straw diameter /mm		
	13	**15**	**17**
The maximum straw cutting force of experiment /N	151	199	241
The maximum straw cutting force of simulation/N	146	184	219
Relative error/%	3.3	7.5	9.1

CONCLUSIONS

A DEM straw model was established based on straw cutting experiment. Firstly, the maximum straw cutting force of the 15mm straw was determined as 199N. Secondly, single factor experiment was used to confirm the factors with significant influence on the maximum straw cutting force namely ball-facet-kn and ball-facet-ks, while other parameters' value was determined, 5×10^3 $N \cdot m^{-1}$ of ball-ball-kn and ball-ball-ks, 2×10^7 $N \cdot m^{-1}$ of pb_kn and pb_ks, 1×10^5 Pa of pb_coh and 5×10^4 Pa of pb_ten.

Regression model was established between the maximum straw cutting force and the significant factors and the regression model was also significant. The best combination value of ball-facet-kn and ball-facet-ks was 17662 $N \cdot m^{-1}$ and 52499 $N \cdot m^{-1}$. Straw cutting verification experiment was conducted with different straw diameters; the results showed that the established DEM straw model could simulate the straw cutting effect, and the relative error of the maximum straw cutting force between the simulation and the experiment was below 9.1%. So, the conclusion can be drawn that the established DEM straw model was accurate and reliable.

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