Simulation and Experimental Analysis of *Camellia oleifera* Fruit Shedding Based on Finite Element Explicit Dynamics

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As an important oil crop in China and the world, the harvesting problem of *Camellia oleifera* has attracted much attention. Research is needed on mechanical characteristics of harvesting equipment. Explicit dynamics was used to establish a finite element model under a simulated load response to the branch-pedicel-fruit system of *C. oleifera* to predict the fracture process at the pedicel junction. The separation mechanism of *C. oleifera* fruit was determined by measuring the constitutive parameters of fruit branches and pedicels and conducting separation experiments and explicit dynamics simulations on different hanging fruits. The maximum stress at the fruit pedicel was 1.14 MPa, and the goodness of fit between the simulation and experiment was approximately 89.5%, indicating that the branch-pedicel-fruit finite element model could accurately reflect the fruit shedding process and that the pedicel diameter was correlated positively with the separation force. This study provides technical parameters for the optimized design of existing *C. oleifera* harvesting equipment.

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Keywords: Explicit dynamics; Finite element simulation; Fruit stem separation force; Camellia oleifera fruit

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INTRODUCTION

As one of the four major woody oils, the fruits and byproducts of *Camellia oleifera* are widely used in edible oil, medicine, health food, daily chemical products, and other industries (Zhang and Wang 2021; Quan *et al*. 2022). Camellia oil processed from *C. oleifera* seeds is rich in natural active ingredients, which have good anti-inflammatory and antioxidant effects and have certain medical value for tumor prevention and gastrointestinal and liver protection (Cheng *et al*. 2015; Liang *et al*. 2017; Xiao *et al*. 2017). However, *C. oleifera* fruit is mainly distributed in the hilly, mountainous, and other complex terrain in the southern region of China (Yan *et al*. 2020). It is difficult to operate large mechanical equipment in the mountains. Consequently, the harvesting operation of *C. oleifera* fruit is mainly by manual fruit picking and shoulder picking baskets (Feng *et al*. 2015; Huang and Rao 2019; Wu *et al*. 2022a). These factors have led to the high price of *C. oleifera* fruit, with harvesting costs accounting for more than half of the total cost of production. If human harvesters repeat this operation for a long time, it is very easy for them to develop lumbar muscle strain, lumbar disc protrusion and other problems (Fathallah 2010). Therefore, mechanized harvesting of *C. oleifera* fruit is a good way to alleviate the defects of the manual harvesting method.

Further research and development of *C. oleifera* fruit harvesting machinery can be expected. In the past, researchers have developed a variety of different mechanized harvesting equipment (Gao *et al*. 2013; Gao *et al*. 2019; Wu *et al*. 2020; Du *et al*. 2022a) for harvesting *C. oleifera* fruit, such as vibrating type, tooth comb type, and roller rubber type equipment (Du *et al*. 2021; Du *et al*. 2022b; Wu *et al*. 2022c). However, because of the biological characteristics of *C. oleifera* fruit, there are some problems, such as insufficient separation force and misharvesting of flowering buds when using mechanized harvesting equipment (Chen *et al*. 2019b). Thus, it is crucial to study the separation mechanism of *C. oleifera* fruit to improve the efficiency of mechanized harvesting of *C. oleifera* fruit (Wu *et al*. 2022b). In addition, there have been few studies that have focused on the biomechanical properties of *C. oleifera* fruits, which leads to the lack of key intrinsic parameters in the analysis process (Rao *et al*. 2017). At the same time, the lack of simulation experiments on the separation of the whole branch models and the lack of basic theoretical studies on simulation experiments affect the reliability and accuracy of the results. Therefore, determining an accurate separation model and the range of separation forces will effectively improve the accuracy and reliability of mechanized harvesting of *C. oleifera* fruits.

To obtain more accurate data on the harvesting of *C. oleifera* fruit and the mechanism of fruit pedicel shedding during picking, this study used explicit dynamics to simulate the stress distribution and fracture mode of the fruit pedicel of *C. oleifera* fruit at the moment of shedding (Zhou *et al*. 2022). A material mechanics model was established based on the physical test of the universal mechanical testing machine. According to the experiments on the separation of two different occasions of hanging fruit, including hanging fruit at the end of the branch and hanging fruit in the branch, the kinetic simulation of the *C. oleifera* fruit picking process was able to determine the separation mechanism and prediction model of *C. oleifera* fruit. The results of the study provide data support for the study of the biomechanical properties of *C. oleifera* fruit as well as the model of the branch-pedicel-fruit system. The results also provide a theoretical basis for the optimization of mechanized *C. oleifera* fruit picking equipment in terms of the specific separation force range and picking method.

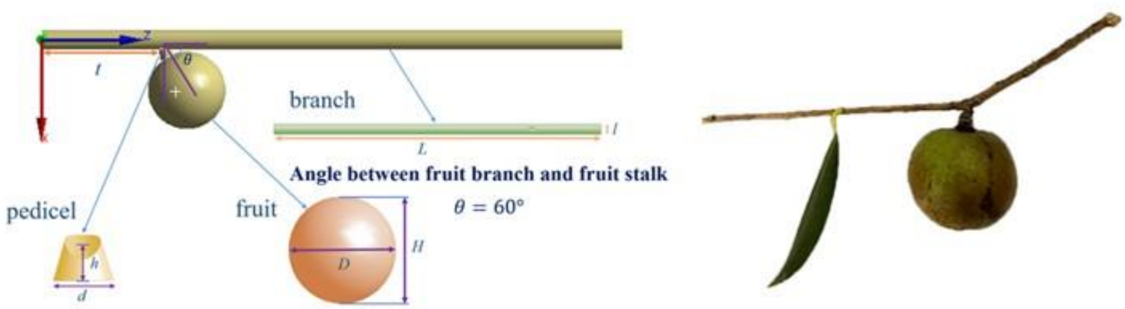
EXPERIMENTAL

Materials

The density, elastic modulus, and Poisson's ratio are important parameters for the simulation of the separation forces of oleaginous fruits. The density of each part is calculated by measuring the mass and volume of the corresponding part. An electronic scale (model: JEA2002; range: 0 to 2000 g; accuracy: 0.01 g; manufactured by Shanghai Puchun Metrology Instruments Co., Ltd. of China) was used to measure the mass. The drainage method was used to measure the volume of each part. An electronic Vernier caliper (model: DL91300; range: 0 to 300 mm; accuracy: 0.01 mm; manufactured by China Deli Group Co., Ltd.) was used to measure the dimensions. Poisson's ratio was obtained according to the relevant literature. Two microcomputer-controlled electronic wood universal testing machines (model: MWD-50; maximum test force: 50 kN; manufactured by Jinan Testing Machine Factory, Jinan, China, Model WDW-10; maximum test force: 10 kN; manufactured by Jinan Testing Machine Co., Ltd.) were used for the testing of the elastic modulus and separation force. To conduct the experiment successfully, the excessive branches were removed from the sample. In addition, corresponding three-point bending and tensile tests were conducted to improve the accuracy of the stress–strain curve.

Explicit Dynamics Modeling

Considering that the deformation and fracture of the pedicel of the *C. oleifera* fruit during the picking process is transient and rapid and the stress distribution, deformation of the pedicel and the fracture mode of the pedicel of the *C. oleifera* fruit at the moment of shedding should be reflected accurately, the explicit dynamics are better for simulating the dynamics model for a short period of time compared to the implicit finite element simulation. The picking model of *C. oleifera* fruit was established by using the Design Modeler module in Ansys. Because the main method of detaching the *C. oleifera* fruit from the fruit branch and the fracture form of the fruit pedicel should be the main concern, a hook-shaped fixture was used for pulling simulation. The branch of *C. oleifera* indicates the penultimate branch of the fruit. The pedicel of *C. oleifera* indicates the connection of the branch and fruit. As shown in Fig. 1, the fruit pedicel was a nonstandard circular table with a small diameter at the end of the fruit branch and a large diameter at the end of the fruit. In addition, the angle between the fruit pedicel and the branch was 60°.



(a) **(b)**

Fruit branch model size parameters (mm)

Project	code	Value(mm)
The pedicel of Camellia oleifera	*d*	3.9
	h	2
The fruit of Camellia oleifera	*D*	20
	H	19.5
The branch of Camellia oleifera	*L*	150
	l	5
Distance between fruit pedicel and bottom of branch	*t*	30

Fig. 1. *Camellia oleifera* fruit: (a) Model, (b) Reference fruit branch

Density

Because the density of the fruit branches and *C. oleifera* fruits could not be measured directly, this paper indirectly measured the ball by measuring their mass and volume. Due to the irregular shape of fruit branches and *C. oleifera* fruits, different diameters at each place cannot be directly calculated by the cylindrical volume formula. Therefore, this research used the drainage method to measure the volume of fruit branches and *C. oleifera* fruits indirectly by measuring the volume of water,

$$\rho = \frac{m}{V} \quad (1)$$

where ρ is the sample density (kg/m^3), m is the sample mass (g), and V is the sample volume (mm^3). The measured sample density is shown in Table 1.

Table 1. Mechanical Parameters of the Material of Each Part of the *Camellia oleifera* Fruit Branches

Item	Density (kg/m^3)	Elastic Modulus (MPa)	Poisson's Ratio
The branch of *C. oleifera*	1190	630	0.30
The pedicel of *C. oleifera*	1190	504	0.30
The fruit of *C. oleifera*	950	—	0.30

Elastic Modulus

The bending modulus of elasticity is an important mechanical parameter of fruit branches, which is a measurement of the ability of fruit branches to resist elastic deformation.

The test was conducted using a WDW-10 microcomputer-controlled electronic wood universal testing machine to measure the bending elastic modulus of *C. oleifera* fruit branches after surface treatment. Because the shape of the fruit branch samples does not meet the sampling criteria "Method for determination of the modulus of elasticity in static bending of wood" (GB1936.2-2009), which requires a specimen size of "300 mm × 20 mm × 20 mm", the bending modulus of elasticity was measured according to the theory of bending beam. By fixing both ends and applying downward pressure to the middle of the fruit branch, the displacement of the point was obtained. The bending modulus of elasticity was calculated using the following equations,

$$f = \frac{Fl^3}{48EI} \quad (2)$$

$$I = \frac{\pi d^4}{64} \quad (3)$$

obtains,

$$E = \frac{4l^3}{3\pi d^4}\left(\frac{\Delta F}{\Delta f}\right) \quad (4)$$

where E is the elastic modulus (MPa), F is the external force (N), d is the sample diameter (mm), l is the span (mm), and f is the deflection (mm). The ratio of external force F and strain ε can be used to calculate the bending modulus of elasticity of the fruit branch. The diameter of the sample branch was measured by calculating the average of the maximum and minimum diameters. As shown in Fig. 2, a three-point bending test was conducted. The span of specimen l was 50 mm, and the speed of the indenter was 10 mm/min.

(a) (b)

Fig. 2. Fruit branch elastic modulus test: (a) Experimental calibration. (b) Branch bending

As shown in Fig. 3, the external force *F* and deflection *f* curve in the bending experiment were obtained. Taking a point within the proportional limit of the curve to record the corresponding external force *F* and deflection *f* data, as shown in Table 2, the average value of the elastic modulus of the fruit branch was calculated at 630 MPa. Because the size of the fruit pedicel was small and short and the elastic modulus of the first level branch was approximately 80% of that of the trunk (Alteryrac *et al*. 2006), the modulus of elasticity of the pedicel was 504 MPa. Similarly, the modulus of elasticity of *C. oleifera* fruit has less influence on the simulation results and can be ignored (Zhao *et al*. 2021).

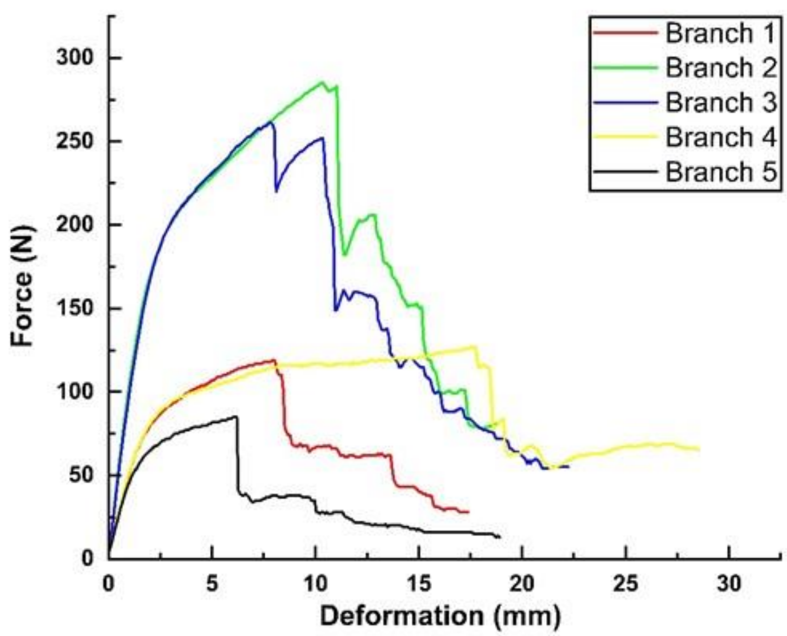


Fig. 3. Results of the three-point bending test on branches

Table 2. Data of Branches Modulus

Number	Diameter (mm)	$\frac{\Delta F}{\Delta f}$ (N/mm)	Elastic Modulus (MPa)
1	8.23	47.9	725
2	9.12	91.6	703
3	8.95	87.6	554
4	8.12	44.4	542
5	7.89	45.6	625

Poisson's Ratio

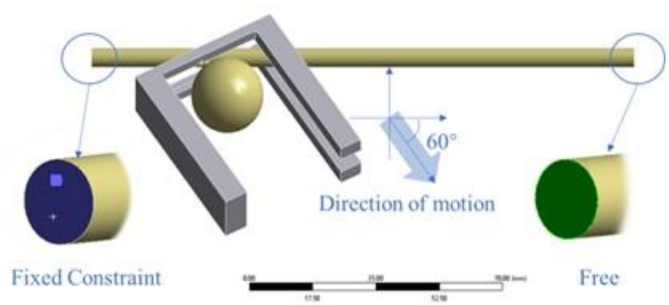
The Poisson's ratio is the ratio of transverse strain to longitudinal strain when an object is subjected to unidirectional tension or compression, and it is a constant that determines the relationship between transverse and axial deformation of an elastic material. Its value is given by Eq. 5,

$$\mu = \left|\frac{\varepsilon_x}{\varepsilon_y}\right| \tag{5}$$

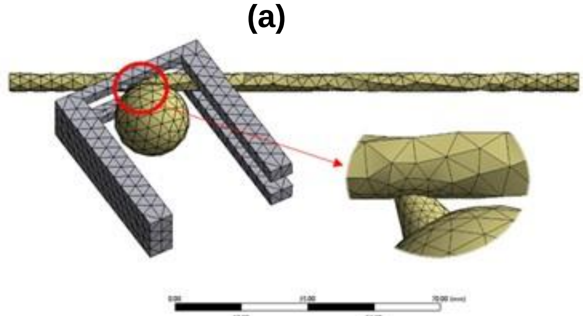
where μ is the Poisson's ratio, ε_x is the deformation perpendicular to the direction of the load, and ε_y is the deformation in the load direction. Because the Poisson's ratio has less influence on the results in the simulation, the Poisson's ratio of fruit branches and fruit pedicels is usually chosen to be 0.3 according to previous studies (Peng and Vázquez-Arellano 2017; Xie *et al*. 2018; Bu *et al*. 2021; Yang *et al*. 2021).

Simulation of *C. oleifera* Fruit Separation Force Based on Explicit Dynamics

After obtaining the parameters in the dynamic simulation through the above experiment, the explicit dynamic module in Ansys was used for the explicit dynamic simulation analysis of the separation principle of *C. oleifera* fruit.



(a)



(b)

Fig. 4. Explicit dynamics simulation: (a) Initial conditions and constraints. (b) Meshing

First, the parameters were brought into the Engineering Material module, and then the *C. oleifera* fruit branch model was imported into the explicit dynamics module. As shown in Fig. 4, the hook and claw jig was used to simulate the process of *C. oleifera* fruit picking.

The jig material, which was set as rigid material, was selected as structural steel, and the contact with the fruit was set as frictionless contact. The mesh sizes of the structural model and fruit pedicel were 4 and 0.8 mm, respectively. In order to better simulate the speed of hand-pulling fruit when picking *C. oleifera* fruit. The speed of the jig was set to 200 mm/s in the direction of the fruit pedicel. The analysis time was set to 80 ms, and the fruit branch support was set to be fixed at one end and free at the other.

RESULTS AND DISCUSSION

Separation Force Simulation Analysis

The equivalent force analysis module was used to output the stress distribution diagram of the *C. oleifera* fruit at the initial stage of abscission, the maximum abscission force stage, and the abscission stage (the fixture was hidden to facilitate the observation of the stress distribution at the fruit pedicel), as shown in Fig. 5. When the fixture was pulled down along the pedicel direction, there was an obvious stress concentration at the fixed end. This is because the branch was constrained to be fixed at one end and free at the other end. Compared with the initial state of the branch in Fig. 5a, there was deformation along the pull-down direction at the hanging fruit section.

The maximum stress of the whole branch was also concentrated in the stressed section, and according to the stress distribution of the pedicel, the stress was mainly concentrated at the joint of the pedicel branch, where the maximum stress value was approximately 1.02 MPa, which was mainly distributed in the upper part of the pedicel and around the fruit hanging section of the branch.

With the movement of the fixture, the joint of the fruit stem and the fruit branch began to be stretched and deformed, and the fracture occurred first at the position where there was high stress concentration of the fruit stem, and then due to the occurrence of the fracture, the fruit stem bent to the fruit branch, and finally caused the fracture between the fruit stem and the fruit branch. As shown in Fig. 5c, in the fruit shedding stage, the branch was fixed at one end and freely restrained at the other. The residual stress at the rear end of the branch was warped, in which the stress change was transferred from the fixed end to the free end.

Therefore, when the *C. oleifera* fruit was stretched by the external force along the pedicel direction, the maximum stress was concentrated at the connection between the pedicel and the branch, and the pedicel fracture was mainly the upper part of the connection fracture.

The stress concentration position obtained by simulation can provide reference for comb clearance and pruning position of comb or pruning *C. oleifera* fruit harvesting equipment. Through the analysis of fracture conditions, it can provide a reference for the fall mode and fall range of the camellia fruit collection device, and further determine the size and force of the collection device.

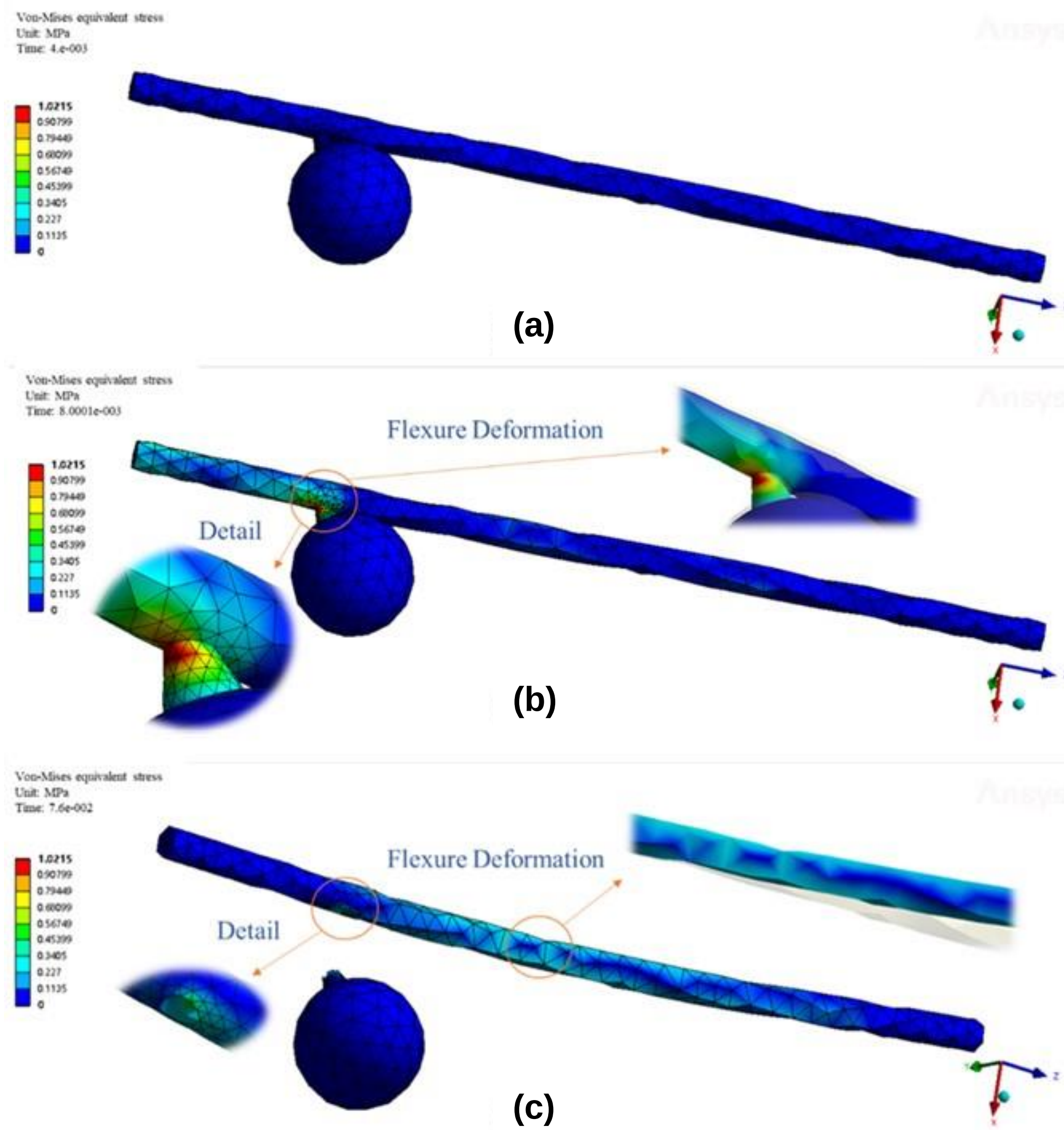


Fig. 5. Results of the explicit dynamics simulation: (a) The stage of early shedding. (b) The stage of maximum shedding force. (c) The stage of shedding

Separating Force Test

The *C. oleifera* fruit selected for the test was from the Changsha artificial experimental forest of camellia fruit in Hunan Province, and the fresh fruit branches within 24 hours of harvesting were studied. In order to better study the stress change of *C. oleifera* fruit stem during actual fracture and the deformation of the stem fracture, a relatively slow test method was adopted to observe and describe the actual fracture of the stem. The tensile test was conducted using a microcomputer-controlled electronic wood universal testing machine to measure the separating force of *C. oleifera* fruit, and the tensile directions in the experiment were all along the pedicel direction. In order to ensure that the tensile direction of the stem is along the direction of the stem in the stem tensile test, the upper clamping position is the branch part and the lower clamping position is the fruit part along the direction of the stem. The measurement process and results are shown in Fig. 6, Table 3, and Table 4. The drawing speed of the fixture was 0.17 mm/s.

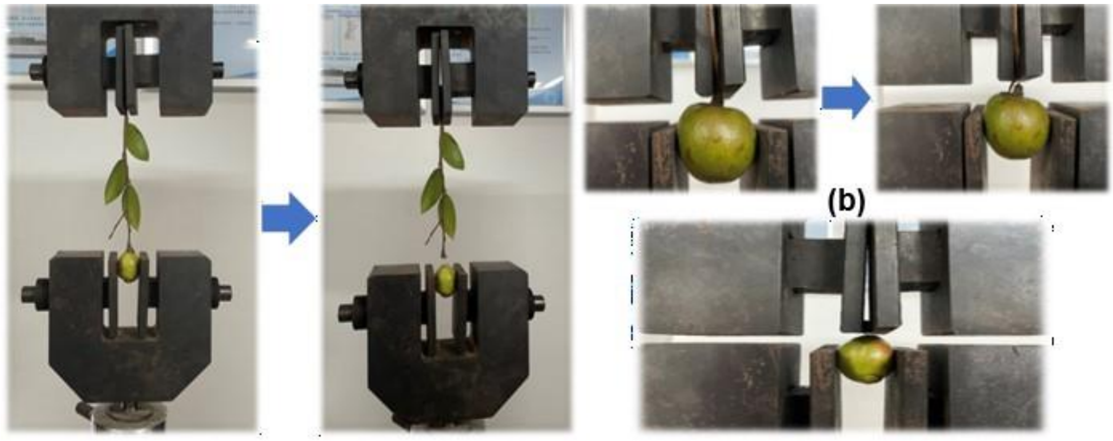


Fig. 6. Tensile test of separation force between the *Camellia oleifera* fruit and the branch: (a) Fruit hanging at the end of the branch. (b) Fruit hanging in the middle of the branch. (c) Separation force test between the pedicel and fruit

Table 3. Data on the Separating Force of Hanging Fruits at the End of Branches

Number	Separation force between branch and pedicel (N)	Separation force between fruit and pedicel (N)	Quality of fruit (g)	Diameter of pedicel (mm)
1	—	24	13.72	3.88
2	20	28	9.21	5.06
3	20	30	21.65	4.71
4	36	58	16.28	5.45
5	12	20	10.16	4.56
6	—	24	13.40	3.97
7	26	30	7.40	5.08

Table 4. Data on the Separating Force of Hanging Fruits in the Branches

Number	Separation force between branch and pedicel (N)	Separation force between fruit and pedicel (N)	Quality of fruit (g)	Diameter of pedicel (mm)
1	34	36	12.70	6.08
2	22	34	25.32	4.81
3	30	32	23.65	5.49
4	20	40	5.49	5.44
5	24	24	5.44	5.15

As shown in Fig. 6a, there were two cases in the separation force experiments on *C. oleifera* fruit branches with fruit hanging at the end of the branch. One was the first breakage between the pedicel and the *C. oleifera* fruit, and the other was the first breakage between the fruit pedicel and the fruit branch. According to Table 3, it was found that the tensile tests of serial numbers 1 and 6 had the case of first breakage between the fruit pedicel and the *C. oleifera* fruit among the seven groups of experiments with fruit hanging at the end of the branch. Compared with the other group, the average diameter of fruit pedicels of these two groups of *C. oleifera* fruit was less than 4 mm. As shown in Fig. 6b, in the separating force test of the *C. oleifera* fruit branches with fruit hanging in the middle of the branches, the fruit was shed by breaking between the pedicel and the branch.

According to the data in Table 3 and Fig. 7, when the fruit hung at the end of the branch, the separating force between the branch and the pedicel ranged from 12 to 36 N, and the average separating force was 22.8 N. The separating force between the pedicel and the fruit ranged from 20 to 58 N, and the average separating force was 30.6 N. As shown in Table 4 and Fig. 7, while the fruit hung in the middle of the branch, the separating force between the branch and the pedicel ranged from 20 to 34 N, and the average separating force was 26 N. The separating force between the pedicel and the fruit ranged from 24 to 40 N, and the average separating force was 33.2 N.

In the case where the point of abscission first occurred at the connection between the pedicel and the branch, the separating force between the pedicel and the branch was smaller than the separating force between the pedicel and the fruit. In addition, there was a case where the separating force was relatively larger for the larger diameter of the pedicel. According to the two sets of separating force data, the separating force between the branch and the pedicel as well as the separating force between the pedicel and the fruit was relatively larger in the case of fruit hanging in the middle of branch compared to the case of fruit hanging at the end of the branch.

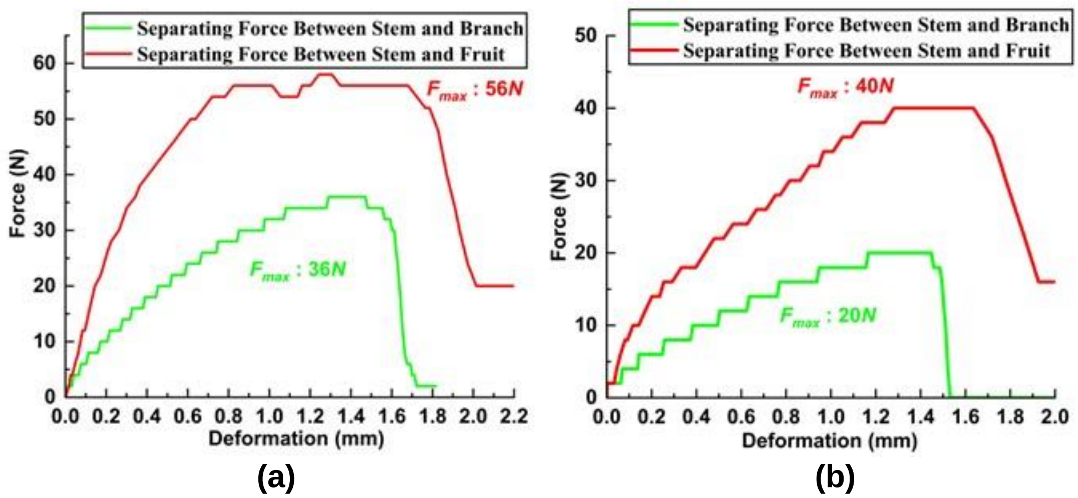


Fig. 7. Curves of separating forces: (a) Fruit hanging at the end of the branch. (b) Fruit hanging in the middle of the branch

According to the stress equation

$$\sigma = \frac{F}{S} \tag{6}$$

where

$$S = \frac{\pi d^2}{4} \tag{7}$$

obtains,

$$\sigma = \frac{4F}{\pi d^2} \tag{8}$$

where F is the separating force (N), S is the cross-sectional area of the fruit pedicel (mm^2), d is the average diameter of the fruit pedicel (mm), and σ is the stress (N/mm^2).

Taking the average value of the separating force between the fruit branch and the fruit pedicel in Table 4 as an example, the force, the standard deviation (SD), and the average diameter of the fruit pedicel were 26 N, 5.21, and 5.39 mm, respectively.

Moreover, the maximum stress value at the connection between the handle and the branch of *C. oleifera* fruit was 1.14 MPa when it is separated. The goodness of fit between this value and the maximum equivalent stress value of 1.02 MPa at the handle in the dynamic simulation was 89.5%. According to the fracture mechanism and stress concentration of the fruit handle in the simulation, the fracture process and results are basically consistent with the separation mechanism of the fruit handle and fruit in the experiment.

Therefore, the simulation of dynamics can be used not only to detect material failure at the pedicel-branch junction but can also accurately simulate the transient process of fruit divorced from the branch during harvesting. Combined with the simulation and experimental results, the maximum stress range of the connection between the fruit and the branch during fruit shedding can be obtained, which can be used to detect the material failure of different types of forest fruit crops and predict the movement process of fruit shedding under vibration, tension, torsion, and other conditions. According to the literature, different picking methods also play an important role in picking efficiency. Some parameters, such as different stretching angles, twisting methods and clamping positions, will affect fruit picking. Hence, we will add more variable parameters in future experiments and simulations to determine a more accurate excitation force, excitation frequency, tensile force, tensile angle, tensile speed, *etc*., to provide a more accurate material mechanics simulation model for the development of high-efficiency and high-precision *C. oleifera* harvesting equipment.

Discussion

In this study, explicit dynamics were used to simulate the fracture mode of *C. oleifera* fruit pedicels when shed. The fracture mechanism of the *C. oleifera* fruit pedicel was explored with different hanging methods. Thus, the knowledge of basic parameters such as the elastic modulus of *C. oleifera* fruit branches was supplemented. The results showed that the stress concentration and fracture mechanism of the pedicel of *C. oleifera* were consistent with the actual shedding condition, and the separation force between the pedicel and fruit was greater than that between the pedicel and branch.

Through experiments, the range of separation forces of *C. oleifera* fruit was determined (Chen *et al*. 2019b; Xie *et al*. 2018; Feng *et al*. 2014). The present results were consistent with previous studies regarding the separation force of *C. oleifera* fruit. Furthermore, based on the separation force, the fracture mechanism of the fruit pedicel was further analyzed in this paper. In terms of the simulation of fruit shedding, the finite element simulation of *C. oleifera* fruit shedding by tooth comb was also carried out before (Rao *et al*. 2017). The study showed stress changes in *C. oleifera* fruit during the process of shedding under the action of tooth comb. When comparing the present results to those of older studies, it must be pointed out that the explicit dynamics have better simulation accuracy, especially for the stress concentration and deformation of the pedicel fracture form under high-speed motion.

However, it was found in some studies that the actual separation force range of *C. oleifera* fruit was quite different (Wu *et al*. 2021), and the separation force of *C. oleifera* fruit in some studies was relatively small (Chen *et al*. 2019b; Li *et al*. 2023). On the one hand, the data of separation force in different studies deviated due to the different varieties of *C. oleifera* fruit; on the other hand, the difference between the maximum and minimum separation force is because although under the same variety, different pedicel diameters and fruit quality have a great influence on the separation force of *C. oleifera* fruit, which is also consistent with the positive correlation between the separation force and the stem diameter found in this paper. The ripeness of fruit also has a certain effect on the separability. According to the literature (Zhu *et al*. 2018; Ye *et al*. 2023), *C. oleifera* fruit has a relatively obvious ripe period, and when the ripeness of *C. oleifera* fruit is low or too high, its oil yield and comprehensive value are low. Therefore, when harvesting, it is generally concentrated in the riper stage of *C. oleifera* fruit. Although there are often less ripe fruits present when the camellia fruit is harvested, their proportion is usually small.

To a certain extent, this paper has filled the lack of constitutive parameters of *C. oleifera* fruit branches and provided a more accurate simulation of *C. oleifera* fruit shedding simulation and basic parameters for various *C. oleifera* fruit harvesting equipment. It is hoped that the simulation of more complex fruit branch shedding can be carried out in future research, and further analysis can be carried out on other operating methods, such as shear and torsion.

CONCLUSIONS

1. The separating force data were brought into the finite element model to provide failure parameters for the separating model. The fruit tensile test and simulation results showed that (1) when the fruit is stretched along the direction of the fruit handle, the stress of the external force load on the fruit handle is mainly concentrated at the pedicel-branch connection; (2) there are different fracture modes of the fruit pedicel under different fruiting conditions. The fruit in the middle of the branch is broken at the pedicel-branch junction, while the fruit at the end of the branch is broken at the pedicel-branch junction or the pedicel-fruit junction. (3) According to the experiment, there is a positive correlation between the maximum separating force and the diameter of the fruit stem.
2. An effective three-dimensional finite element model of the branch-stand-fruit system was established by measuring the constitutive parameters of *Camellia oleifera* branches, *C. oleifera* fruit pedicels, and the abscission zone. Second, the fracture process of the pedicel-branch joint was visually simulated by means of explicit dynamics, which reflected the transient changes in stress and deformation at the pedicel-branch joint at the moment of *C. oleifera* fruit removal. Then, the separating force test was carried out with a universal testing machine, and the experimental data in the actual tensile process were obtained.
3. In this paper, the maximum stress of fruit pedicel separation is further analyzed by using the finite element simulation results. Compared with the tensile test results, the goodness of fit of the maximum stress is approximately 89.5%, indicating that the branch-stand-fruit finite element model can accurately reflect the fruit separation process. This study provides a reliable finite element model of a branch-pedicel-fruit system for future research on *C. oleifera* vibration harvesters or robot harvesters.

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