ASSESSMENT OF APPLE DAMAGE CAUSED BY A FLEXIBLE END-EFFECTOR / 柔性末端执行器抓握过程苹果损伤评估

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ABSTRACT
In recent years, apple harvesters have become a research hotspot. Interaction control between the robot end-effector and the fruit is crucial to reduce mechanical damage to the fruit and achieve high picking performance. In this article, the damage degree was also quantified using a damage factor based on the damage plasticity model. A flexible three-finger end-effector was designed based on the Fin-Ray effect, and finite element models were established in ABAQUS to simulate the cortex damage during grasping. The results showed that the maximum von Mises stress was 0.159 MPa for the apple skin, 0.082 MPa for the cortex, and 4.178 N for the contact force, respectively. The result of the verification test showed that the maximum contact force was 4.572 N, and the relative error between the simulation and experimental results was 8.62%. Simulation and verification tests showed that the flexible three-finger end-effector achieved non-destructive grasping of apples.

摘要
近年来，苹果收获机器人成为研究热点，收获过程中末端执行器与果实的交互作用控制对减少果实损伤起到至关重要的作用。本文基于果肉的损伤塑性模型，测算了果肉在拉伸和压缩过程中的损伤因子，量化了损伤程度；基于鳍条效应设计了柔性三指末端执行器，并建立了末端执行器和苹果的有限元模型。仿真结果表明，果皮 Mises 最大应力为 0.159 MPa，果肉最大应力为 0.082MPa，接触压力最大为 4.178N。验证试验中，最大接触力为 4.572 N。最大接触力仿真值与实际最大接触力的误差为 8.62%。仿真与验证试验均表明该柔性三指末端执行器可以实现苹果的无损抓取。

INTRODUCTION
The China Agriculture Yearbook of 2019 indicates that the apple planting area in China was 1.94 million hectares, accounting for 16.3% of the national planting area, making China the world's largest apple producer. Furthermore, apple production reached 39.233 million metric tons, accounting for 22.3% of the total fruit production. Apple harvesting is both time- and labour-intensive, and the workers require experience and skill. Since the 20th century, a reduction in agricultural employment has posed a serious challenge in many countries. Mechanization could be a solution to tackle this problem in the fruit industry. In recent years, apple harvesters have become a research hotspot. Interaction control between the robot end-effector and the fruit is crucial to reduce the mechanical damage to the fruit and achieve high picking performance.

Owing to the integration of finite element software and enhanced visualization, finite element analysis has become an effective method. A drop test simulation was used to optimize the material, height, and direction of the fruit collection units *(Lewis, Yoxall, Canty et al., 2007; Celik, Rennie, Akinci, 2011)*. Compression and impact were used to simulate dynamic and static load states during fruit transport *(Lewis, Yoxall, Marshall et al., 2008; Dintwa, Van Zeebroeck, Ramon, 2008).* In particular, *Dintwa, Van Zeebroeck, Ramon et al., (2008)* pointed out that the viscoelastic properties obtained from stress relaxation experiments were not applicable to describe the transient behaviour of fruits, and a highly accurate theoretical evaluation was required. *Ji W., Qian Z., Xu B. et al., (2019),* analysed the viscoelastic response of different parts of the fruit at different velocities of the grasp and estimated the equivalent stress when plastic damage occurred.

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Ahmadi, Barikloo and Kashfi M. (2016) considered a nonlinear time-dependent contact in the modelling of fruit-plane collision and fruit-fruit collision and analysed the influence of the mechanical properties, shape, size, and relative velocity of the object on the kinetic energy loss of the fruit collision.

In contrast, a simpler and more effective method to eliminate the effects of 'hard contact' is the use of a flexible gripper. In this study, a flexible three-finger end-effector was designed based on the Fin-Ray effect, and the parameters of the Ogden third-order model were obtained through the stress-strain response of the thermoplastic polyurethane (TPU) material. Based on the damage plasticity model, the stress-strain response behaviour of the apple cortex during stretching and compression was tested. Furthermore, finite element models of the apple and end-effector were established using ABAQUS software and the material parameters to simulate cortex damage during grasping and evaluate the feasibility of the proposed end-effector.

MATERIALS AND METHODS

End-effector design

The design principles of the end-effector include a simplified structure, improved grasping reliability, and prevention of damage to the fruit. The end-effector consists of a stepping motor, a moving plant, links, finger mounts, soft fingers, and a base frame, as shown in Fig. 1(a). The moving plate, links, and the frame consist of aluminium alloy, and the finger mounts are made of plastic. Flexible fingers are designed based on the fin effect with a V-shaped skeleton structure embedded in a series of supports. The soft fingers made of TPU material (Shall hardness 90 HA) were 3d printed by WeiLaiGongChang Co., Shenzhen, Guangdong, as shown in Fig. 1(b). The characteristic of this structure is that when one side is subjected to a force, the free end will bend in the opposite direction of the force applied so that the side surface of the skeleton is closely attached to the grasped object, forming an effective grip *(Crooks, Vukasin, O'Sullivan et al., 2016; Crooks, Rozen-Lev, Trimmer et al., 2017; Elgeneidy et al., 2019; Shan and Birglen L., 2020)*. In the no-load condition, the stepping motor drives the moving plate to translate, making the finger mount rotate 0.5 rad within 0.5 s.

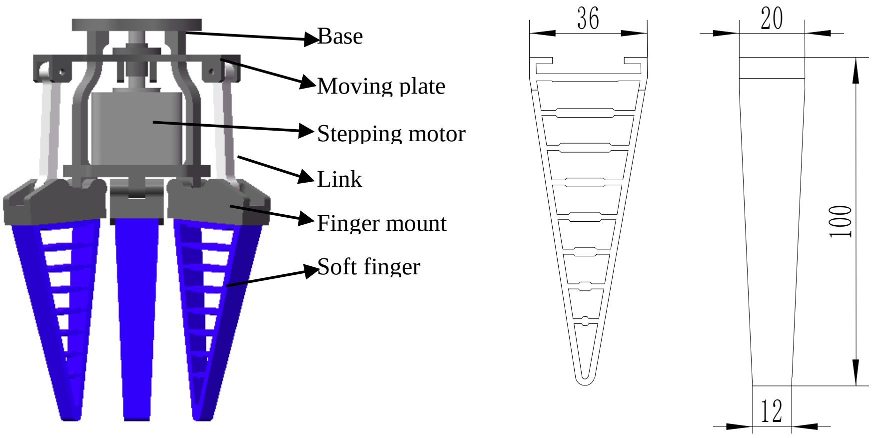


Fig. 1 - Schematic drawing of end-effector structure (a) and the soft finger (b)

TPU mechanical properties

The tensile tests were conducted on an electronic universal testing machine (type: DDL10, range: 0-10 kN; manufactured by Sino test Equipment Co., Ltd., China). The samples of the tensile tests were prepared according to the ISO 37-2011 standard. A loading rate of 500 mm/min was applied in the tensile tests. The stress-strain response results of the tensile test were used to fit the mathematical model. As a widely used mathematical model, the Ogden model *(Ogden R.W., 1972)* provides a good fit to the test data within a strain of 700% *(Kim B., Lee S.B., Lee J. et al. 2012)*. Therefore, the Ogden 3N model was used to fit the experimental results. The strain energy density function is defined as follows *(SIMULIA 2018)*:

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i} (\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) \quad (1)$$

where λ_j (j=1,2,3) are the principal stretch ratio; N is a material parameter; μ_i and α_i are empirically determined material constants.

The experimental data fitting of the mathematical model was performed using ABAQUS 2018 software (version 2018, Dassault Systemes Simulia Corp., USA).

Apple cortex mechanical properties

The mechanical properties of the apple cortex were measured by tensile and compression tests to estimate the degree of damage during stretching and compression, respectively of the apple cortex. The tensile tests and compression tests followed the standard (ASAE S368.4 DEC2000, 2017) and were conducted on an electronic universal testing machine with a loading speed of 3 mm/min (0.05 mm/s). The test samples were Pink Lady apples picked in November 2019. The samples for the compression test were cylinders, and the samples for the tensile test were cylinders cut into type I. The test samples and their shape parameters are shown in Fig. 2 and Table 1. Each group of experiments was repeated ten times.

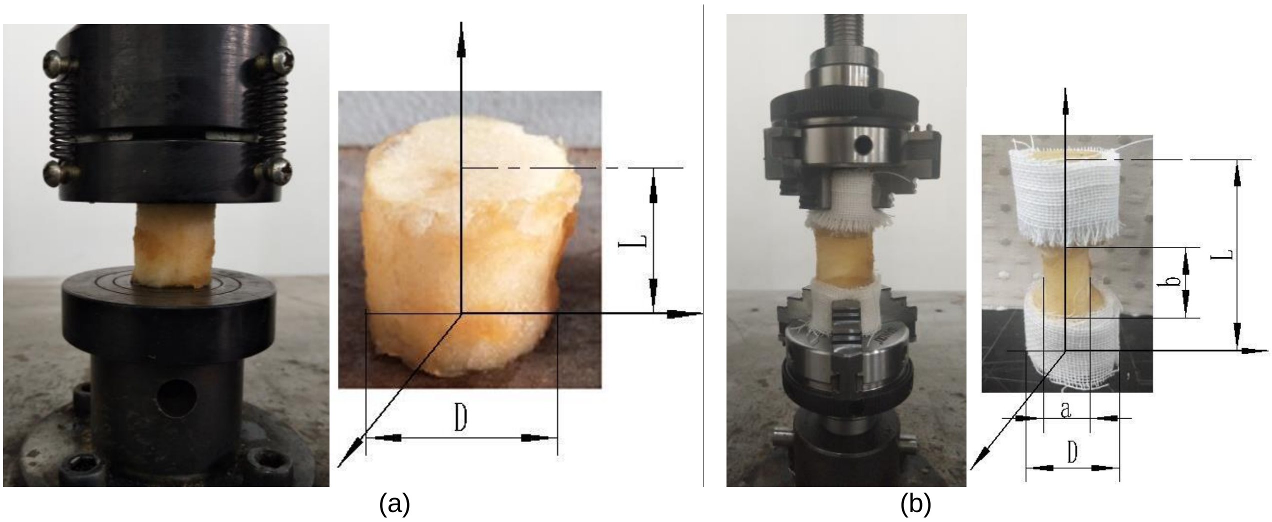


Fig. 2 - Cortex samples for compression test (a) and tensile test (b)

Table 1

Shape parameters of cortex samples

	L [mm]	D [mm]	a [mm]	b [mm]
Cortex samples for compression test	21.457±0.343	21.050±0.074	-	-
Cortex samples for tensile test	60.434±0.535	21.079±0.103	9.977±0.501	26.832±1.013

The damage plasticity model was used to describe the response behaviour of the cortex during stretching and compression and quantify the degree of apple cortex damage, as shown in Fig. 3. Based on the energy equivalence principle *(Sidoroff F., 1982)*, the damage factor d was calculated (Eqs. (2)-(5)) and represented the damage degree of the apple cortex.

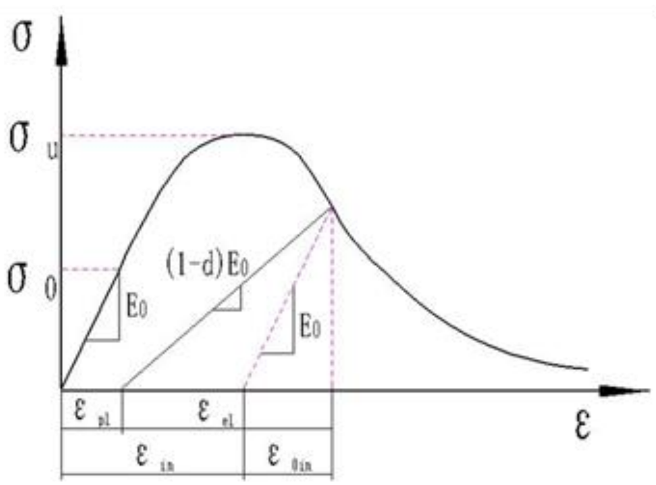


Fig. 3 - Schematic diagram of damaged-plasticity model

$$\varepsilon^{in} = \varepsilon - \varepsilon_0^{el} \tag{2}$$

$$\varepsilon_0^{el} = \frac{\sigma}{E_0} \tag{3}$$

$$\varepsilon^{pl} = \varepsilon^{in} - \frac{d}{1-d}\varepsilon_0^{el} \tag{4}$$

$$d = 1 - \sqrt{\frac{\sigma}{E_0 \varepsilon}} \tag{5}$$

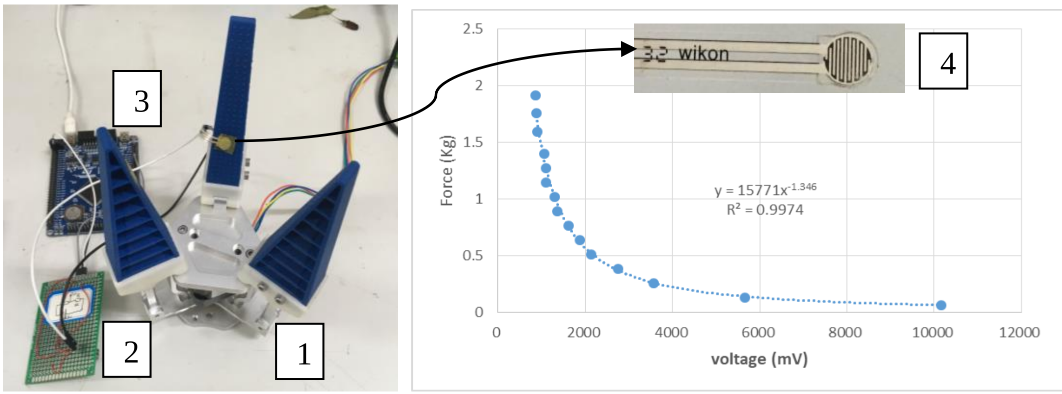
Where:

ε^{in} is the inelastic strain, $\varepsilon^{el}{}_0$ is the elastic strain for the initial stiffness E_0, ε^{pl} is plastic strain, and d is the damage factor.

Simulation and verification test of dynamic grasping process of the end-effector

A 3D apple model consisting of the skin, cortex, and core was established using SolidWorks (version 2018, Dassault Systemes Simulia Corp., USA). The physical measurements of the apples were obtained applied from a previous work *(Bu L., Hu G., Chen C. et al., 2020)*. The reconstructed model was imported into Abaqus Software (version 2018, Dassault Systemes Simulia Corp., USA), and the material properties were defined. The material parameters are listed in Table 2. The end-effector was simplified as three fingers and their mounts. The soft fingers were meshed into 6933, 6953, and 6884 elements, respectively. Meanwhile, the mounts were meshed into 13964, 14778, and 14819 elements. The number of elements of the skin, cortex, and core were 12409, 37150, and 7313, respectively. All the elements were C3D4 (4-node linear tetrahedron) cells. The rotation speed of the soft finger was set at 1 rad/s for 0.5 s. The normal behaviour of the finger-skin contact was set to hard contact, and the tangential friction coefficient was 0.3. The Von Mises stress, contact stress, and contact force were the outputs of the simulation.

The test device is shown in Figure 4a. In addition to the end-effector (1), a thin-film pressure sensor (4) was attached to the soft finger. An STM32 Microcontroller (3) converted the signal from the voltage output module (2) to the pressure signal. The relationship between voltage and pressure is shown in Figure 4(b).



(a) (b)

Fig. 4 - Schematic diagram of the test device (a) and voltage and pressure diagram after calibration (b)

1 - end-effector; 2 - voltage output module; 3 - STM32 Microcontroller; 4 - thin-film pressure sensor

RESULTS AND DISCUSSION

Stress-strain characteristics of TPU

The comparison of the tensile test results and the Ogden 3N model fitting is shown in Fig. 5. The tensile test result shows that the stress increases nonlinearly with the strain; the strain of the sample exceeds 460% with stress of over 25 MPa when the fracture occurs. Compared with the experimental results, the fitting results of the Ogden 3N model show relatively good accuracy within strain values of 300%.

The parameters of the Ogden 3N model are shown in Table 2.

So far, the material characteristics of apple cortex and TPU have been mentioned, and the parameters of relevant materials used for simulation are listed in Table 2.

Mechanics parameters of the materials **Table 2**

	Density [kg/m³]	μ_i	α_i
TPU	120	-8.00934697	3.11633812
		4.79631477	3.34227895
		10.0632388	-5.22676310
	Density [kg/m³]	**Elasticity modulus E [MPa]**	**Poisson's ratio u**
Aluminium alloy[a]	2750	69000	0.35
plastic[b]	120	2388	0.37
cortex	840	3	0.35
skin[c]	840	12	0.35
core[c]	950	7	0.35

a: data from *(Liu, Y., Liu, H., Chen, Z., et al. 2019)*
b: data from *(Pastor-Artigues, M.-M., Roure-Fernández, F., Ayneto-Gubert, X., et al. 2020)*
c: data from *(Ahmadi, E., Barikloo, H., and Kashfi, M., 2016)*

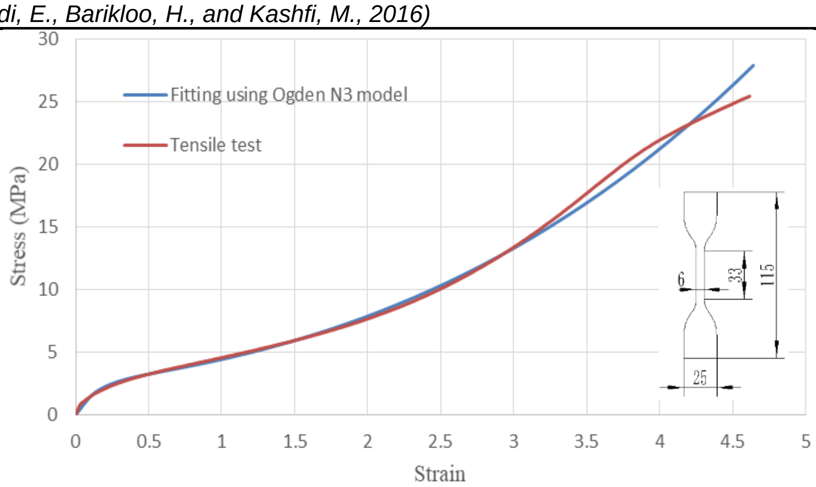


Fig. 5 - Strain-stress curve of the tensile tests and fitting using the Ogden N3 model of the TPU specimen

Stress-strain characteristics of apple cortex

The responses of the apple cortex to stretching and compression are different, as shown in Figure 6.

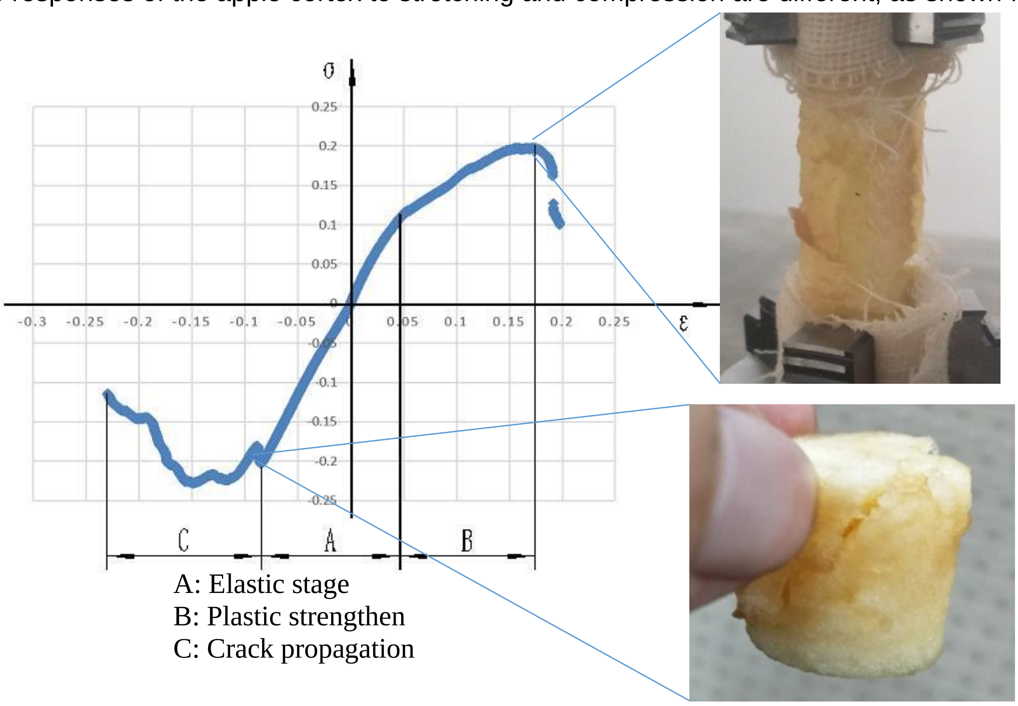


Fig. 6 - The stress-strain curve of the apple cortex during the tensile test and compression test

The elastic modulus E_0 of the elastic stage is 2.33 ± 0.46 MPa, which is smaller than that reported by *Ji W., Li J., Yang J. et al., (2015), Ji W., Qian Z., Xu B. et al., (2017), Ahmadi E., Barikloo H., Kashfi M. et al., (2016)*. Possible reasons include the apple variety and texture differences. During the tensile test, the cortex shows the characteristics of bilinear strengthening; the yield stress is about 0.1 MPa, and the strength limit is about 0.2 MPa. In the compression process, the sample cracked at an inclination angle of 45° due to shear failure when the stress was 0.2 MPa and then continued to collapse until complete failure occurred. This result is consistent with those of *Khan A.A. and Vincent, (1993), Holt J, and Schoorl D., (1982)*.

Figure 7 presents the correlation between the damage factor and the inelastic strain. In the tensile test, fracture failure occurred after significant yielding had occurred. The reason was intercellular damage in addition to the expansion of the pores during the stretching process; thus, the pulp damage factor was less than 0.6 when the fracture occurred. Meanwhile, during compression, after the occurrence of fault cracks along the 45° inclined plane, the stiffness began to decrease significantly because the cells were gradually crushed and failed, and the damage factor continued to rise.

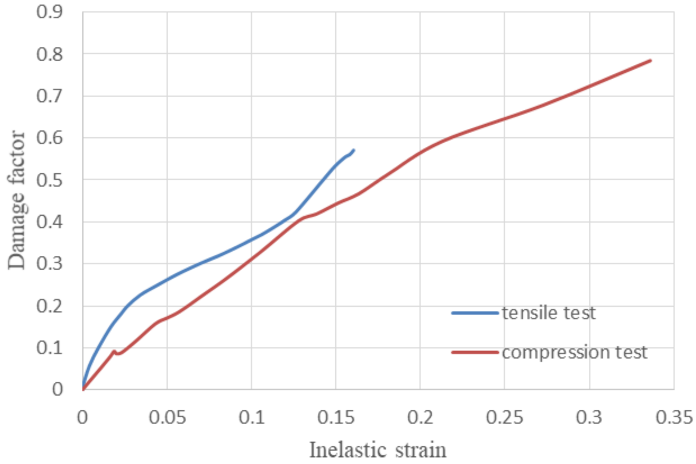
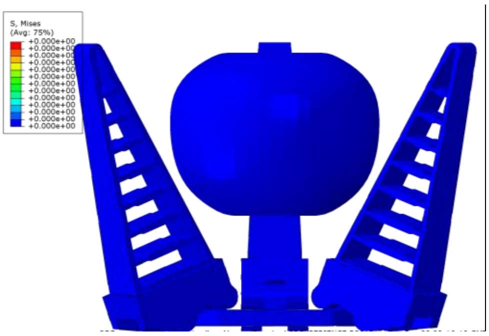


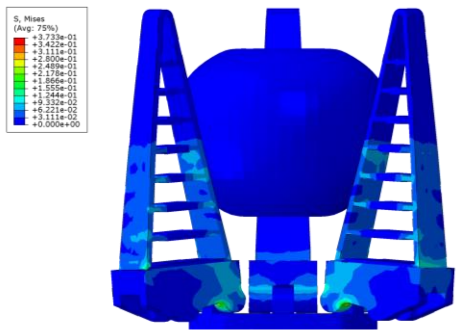
Fig. 7 - Correlation between the damage factor and the inelastic strain during the tensile test and compression test

<u>**Simulation results and experimental verification**</u>

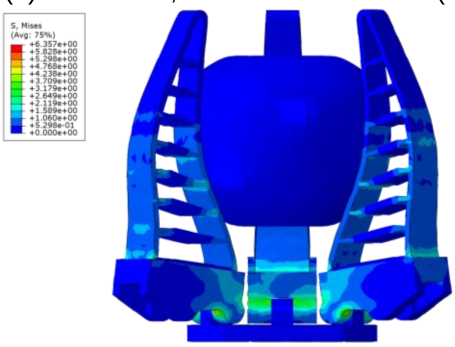
Figure 8(a), (b), and (c) show the von Mises stress results of the grasping process of the end-effector obtained from the finite element analysis.



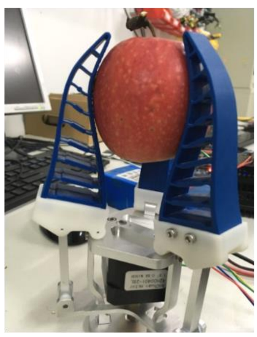
(a) initial state, t=0s



(b) beginning to touch, t=0.27s



(c) grasping termination, t=0.5s



(d) verification result

Fig. 8 - Stress cloud diagram of the grasping process of the end-effector in the simulation and verification test

As shown in Fig. 9, in the simulation experiment, the soft finger contacts the apple at about 0.27 s, and the contact stress and contact force gradually increase. At about 0.325 s, the contact stress and contact force of the pericarp suddenly drop due to tangential slippage. Then the contact stress and contact force gradually rise until the simulation ends and reach the maximum value; the maximum values of the contact stress and contact force are 0.159 MPa and 4.178 N, respectively. In addition, the maximum von Mises stress of the apple cortex is 0.082 MPa, which is considerably less than 0.2 MPa, which may cause damage. A comparison of the contact force in the simulation and the verification test shows the same trend, which also reflects the process of tangential slippage. The maximum contact force in the verification test is 4.572 N, with a relative error of 8.62% compared with the simulated value. The error could be due to the irregular shape of the apple and the placement of the pressure sensor.

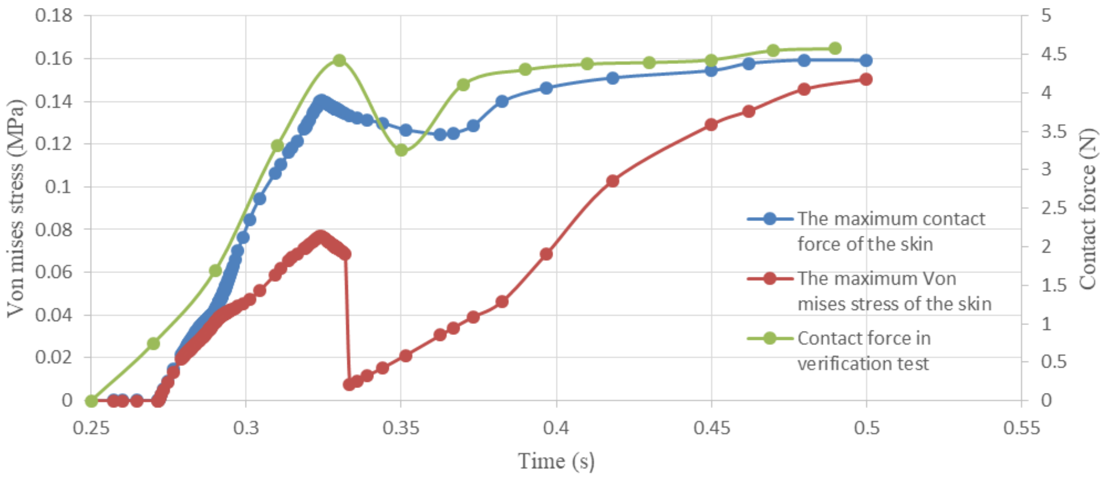


Fig. 9 – Simulation results of the maximum Von Mises stress and maximum contact force of the apple skin

CONCLUSIONS

In this study, the damage factor of the apple cortex during stretching and compression was calculated based on the damage plasticity model, and the damage degree was quantified. A flexible three-finger end-effector was designed based on the Fin-Ray effect, and the parameters of the Ogden third-order model were obtained from the stress-strain response of the TPU material. Based on the material properties, a finite element model of the apple and end-effector was established using ABAQUS software to simulate the cortex damage during grasping. The results showed that the maximum von Mises stress was 0.159 MPa for the apple skin, 0.082 MPa for the cortex, and 4.178 N for the contact force. In the verification test, the thin-film pressure sensor was mounted at the position of the maximum contact force in the simulation test, and the maximum contact force was 4.572 N. The error between the simulated value and the experimental value of the maximum contact force was 8.62%. Simulation and verification tests showed that the flexible three-finger end-effector achieved non-destructive grasping of the apple.

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