

## Research Article

### Experimental Study on Preserved Egg Breakage Mechanism and Finite Element Analysis

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**Abstract:** Preserved egg shell is easily broken, The premise is to obtain physical properties and mechanical properties of preserved egg each structure to analyze its breakage mechanism. We apply the method of differential and integral calculus to calculate the basic physical quantities and changes in relationships between them by non-standard elliptical appearance, such as particle size, surface area, cross-sectional area, volume and the perimeter; Through mechanics test, we analyze the breakage rate at 10~30 mm/min five different loading rates by the whole eggs and egg shell; We analyze the stress and strain condition and check the accuracy of experiments by finite element simulation analysis through their workbench model. The results both experimental value and simulation value show the mechanical properties of preserved egg present the regularity of changes by different structures, loading rates and loading directions. These finding suggest that the breakage mechanism of preserved egg is highly dependent on the fracture strength, unit deformation and fracture energy under a certain physical characteristics. Moreover, it was found that these mechanical characteristics were highly dependent on the structure, loading rate and loading direction.

**Keywords:** Mechanical properties, physical properties, preserved eggs, the finite element analysis

## INTRODUCTION

Preserved egg shell is brittle and broken easily. Data showed: The breakage rate of preserved eggs up to 11~14% in production, circulation and other link, only 2~3% breakage in the duck egg output, 9~11% in cleaning, packaging, processing, loading and unloading and transportation link. Broken egg not only would lost all or part of its economic value and use value, but could bred ground for harmful organisms, polluted other preserved eggs and caused potential safety hazard. According to the structure characteristics of the preserved egg, its damage mechanism were explored by the theory contains compression test, computer simulation and finite element analysis, to reduce its breakage and the optimization design related processing equipment is of important significance.

Scholars at home and abroad carried out experimental study on the basis of the key physical parameters affecting egg breakage. The research on eggs of different quality on its physical properties and mechanical properties is of great significance (Altuntas and Sekeroglu, 2010). The research on the biomechanical characteristics of the egg shell is done (Entwistle *et al.*, 1995). The effect of egg shape index on mechanical properties of chicken eggs through experiments (Altuntas and Sekeroglu, 2008). At present, there were few reports about the characteristic of single structure and the finite element analysis of preserved egg. In this study, the physical properties of

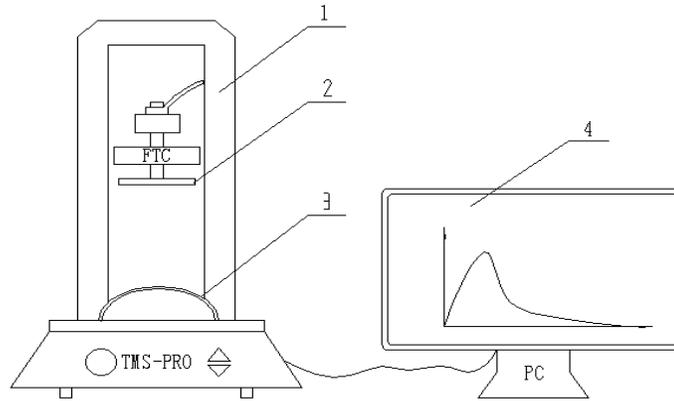
preserved egg were determined, the mechanical properties of different loading direction and the finite element simulation analysis of each structure were tested and analyzed. To find preserved egg breakage mechanism and regularity, put forward impairment measures in each link of preserved egg.

## EQUIPMENT, MATERIALS AND METHODS

**Experiment equipment (Fig. 1):** Astral instrument (the FTC company TMS-PRO, load 0~1000 N, precision of  $\pm 1\%$ ), Shell thickness tester (manufacturers Orka Technology Ltd., resolution from 0.001 inches to 0.01 mm; test range: 0.15 mm to 25.40 mm), Person computer, the electronic scale, vernier caliper, knives.

**Experimental materials:** Some preserved eggs from Hubei Shendan health food co., LTD, at room temperature of 200 c, to reduce the random error caused by different size, preserved egg size was select for the short axis 44.0~45.0 mm, long axis 59.5~60.5 mm, egg weight 50.0~55.0 g.

Selecting the samples 400 pieces and dividing into two parts: The whole eggs and the egg shell (Fig. 2). They were compressed from equator, tips and blunt end three directions by five arithmetic rates (10 mm/min-30 mm/min). To record its parameters such as fracture force, deformation and fracture energy, statistic its testing results and analyze its physical properties and damage mechanism.



1-Texture analyzer 2-Load sensor 3-The object is loaded (preserved egg) 4-PC

Fig. 1: Preserved egg loading test bench (1-Texture analyzer 2-Load sensor 3-The object is loaded (preserved egg) 4-PC)

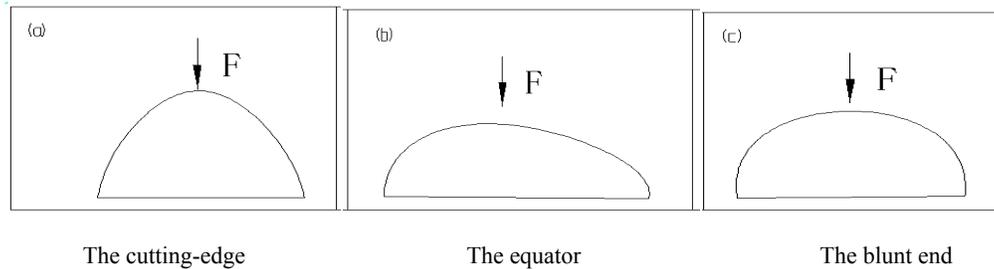


Fig. 2: Preserved egg loading diagram of each structure

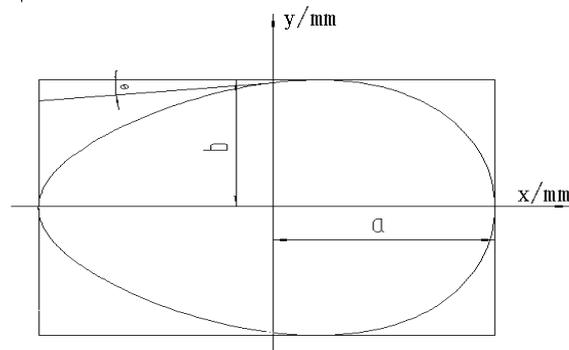


Fig. 3: Preserved egg appearance size schematic diagram

**Preserved egg appearance size measurement:** Preserved egg is non-standard ellipse object (Fig. 3), The contour curve is shown in Formula (1). Among them: A denotes long half shaft size, b denotes short half shaft size, Unit: mm.  $\theta$  denotes egg-shaped angle, Unit: degree:

$$\frac{x^2}{a^2} + \frac{y^2}{(b + x \cdot \tan \theta)^2} = 1 \quad (1)$$

**Physical characteristics:** Preserved egg of physical characteristics can be divided into the physical characteristics of the non-damaged condition and mechanical characteristics of the damaged condition.

The former includes size, particle size, surface area, cross-sectional area, volume and the perimeter. We use mathematical method (Formula 1). The latter includes the fracture force, unit quantities and fracture energy when damaging.

**Physical characteristics:** Particle size refers to the ellipsoid spherical equivalent as minimum diameter, its size depends on the shaft size. The experiment samples select randomly and measure the size of long axis (a) and short axis (b) (Formula 2):

$$D_g = 2(ab^2)^{\frac{1}{3}} \quad (2)$$

The available:

$$S_g = \frac{D_g}{2a} \quad (3)$$

$$S_a = \pi^2 ab + \frac{2}{3} \pi a^2 \tan \theta \quad (4)$$

$$S_c = \pi ab + \frac{2}{3} \tan \theta \cdot a^2 \quad (5)$$

$$V = \pi \left( \frac{4}{3} ab^2 + \frac{4}{15} a^3 \tan^2 \theta \right) \quad (6)$$

$$L = \int_a^a \sqrt{1 + (f'(x))^2} dx = \pi \cdot D_g \quad (7)$$

where,

$S_g$  : Sphericity of the geometry, dimensionless

$S_a$  : Surface area of the geometry, Unit:  $\text{mm}^2$

$S_c$  : Cross-sectional area of the geometry, especially along the long axis of the preserved egg, Units:  $\text{mm}^2$

$V$  : Volume of the geometry, Units:  $\text{mm}^3$

$L$  : Circumference of the outer contour of the geometric, especially the long axis direction of the preserved egg, Unit: mm

**The mechanical characteristics:** contain the fracture force, unit quantities and fracture energy when damaging:

$$\varepsilon = \frac{L_o - L_d}{L_o} \times 100 \% \quad (8)$$

$$E = \int_0^s (F \cdot s) ds \quad (9)$$

where,

$\varepsilon$  : Unit deformation of the material in the process when compressing, dimensionless

$L_o$  : The original length before compressing, Unit: mm.

$L_d$  : The length after compressing, Unit: mm

$E$  : Fracture energy of the material when bursting, Unit: mJ

$F$  : Fracture force of the material when bursting, Unit: N

$S$  : Displacement of the material when bursting, Unit: mm

## RESULTS AND DISCUSSION

**Physical characteristics:** The calculation means consider egg-shaped Angle of preserved egg's apparent physical parameters were more accurate in Table 1. The linear analysis among the sphericity, surface area,

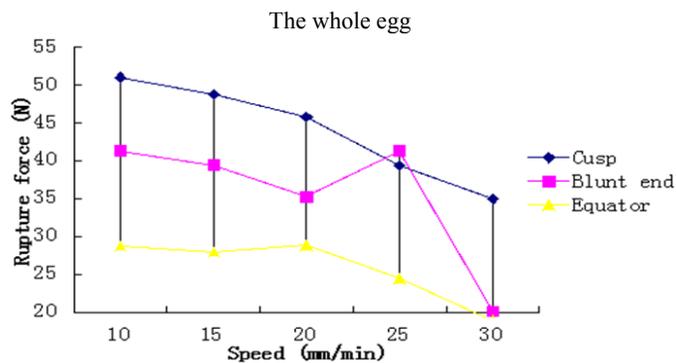
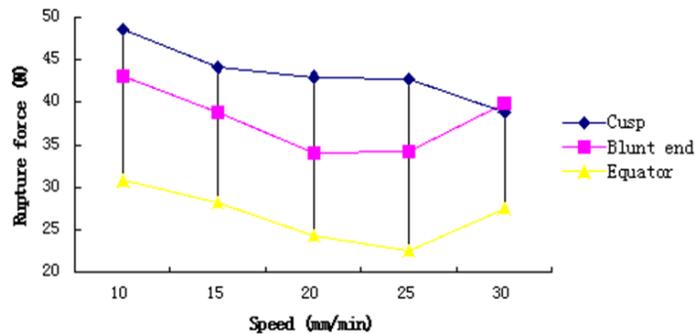
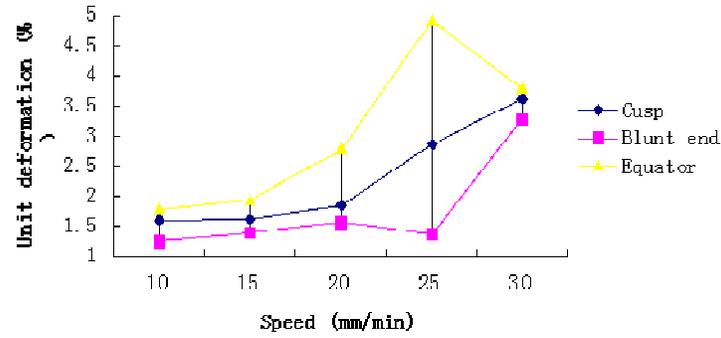
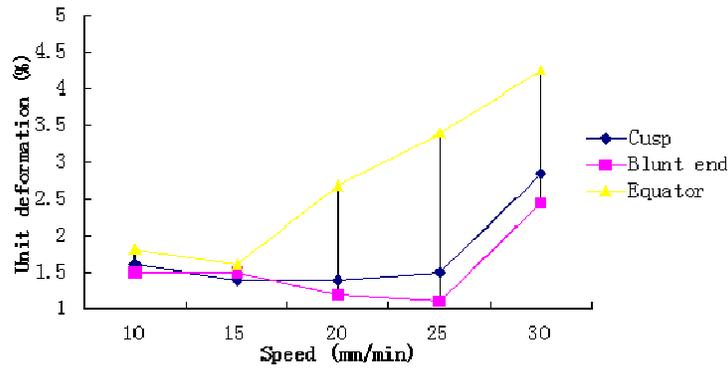


Fig. 4: Fracture force with the change by the loading directions and loading rates of preserved egg

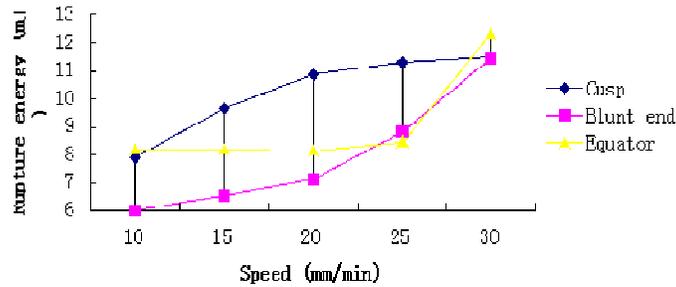


The whole egg

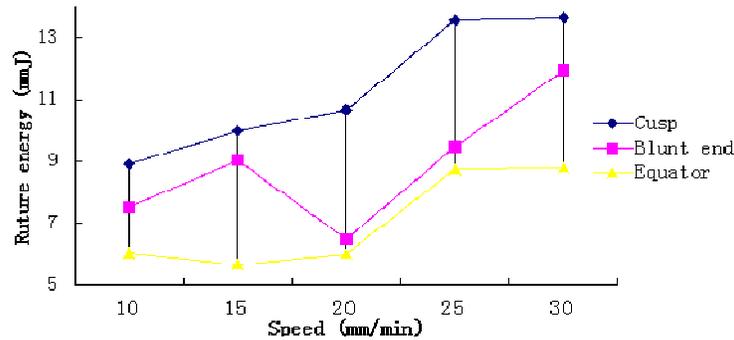


The egg shell

Fig. 5: Unit deformation with the change by the loading directions and loading rates of preserved egg



The whole egg



The egg shell

Fig. 6: Fracture energy with the change by the loading directions and loading rates of preserved egg

Table 1: Preserved egg apparent physical parameters

|       | Long axis (mm) | Short axis (mm) | Egg weight (g) | Thickness of eggshell (mm) | Particle size (mm) | Sphericity | Surface area (mm <sup>2</sup> ) | Cross area (mm <sup>2</sup> ) | Volume (mm <sup>3</sup> ) | Perimeter (mm) |
|-------|----------------|-----------------|----------------|----------------------------|--------------------|------------|---------------------------------|-------------------------------|---------------------------|----------------|
| MAX.  | 60.98          | 46.04           | 71.97          | 0.513                      | 50.40              | 0.842      | 6871                            | 2294                          | 67714                     | 158.25         |
| MIN.  | 59.14          | 44.02           | 64.94          | 0.461                      | 48.76              | 0.8061     | 6496                            | 2172                          | 61359                     | 153.10         |
| AVE.  | 60.04          | 44.84           | 67.83          | 0.485                      | 49.425             | 0.8231     | 6642                            | 2219                          | 63899                     | 155.19         |
| STDEV | 0.5005         | 0.5205          | 1.682          | 0.004                      | 0.3694             | 0.008770   | 81.70                           | 26.79                         | 1424                      | 1.16           |

Table 2: Preserved egg apparent physical parameters

| Indicators      | Linear equation       | Significant judgment                 |
|-----------------|-----------------------|--------------------------------------|
| Surface area/Sa | Sa = 208.30Dg-3650.9  | R <sup>2</sup> = 0.8870, significant |
| Cross area/Sc   | Sc = 66.74Dg-1078.5   | R <sup>2</sup> = 0.8466, significant |
| Volume/V        | V = 3857.20 Dg-130000 | R <sup>2</sup> = 0.9980, significant |
| Perimeter/L     | L = 3.14Dg+4.3*10-10  | R <sup>2</sup> = 1.0000, significant |

cross-sectional area, volume and perimeter with the particle size of preserved egg by experiment were measured in Table 2, The result shows that this method is extremely significant (p<0.01), it is feasible and high precision.

**Mechanical properties:**

**Strength:** The fracture strength with the change of loading rate and the direction of whole egg and egg shell in Fig. 4. The probe can measure the fracture strength of the loaded object when loading into a certain size, the fracture strength of the whole egg was ranged from 22.6 N to 48.6 N, egg shell was ranged from 18.9N to 51 N. As the loads increased from 10 mm/min to 30 mm/min, the fracture strength decreased in each loading direction. For the whole egg and egg shell, the fracture force of the cup and blunt end is bigger than the equator in the same compression direction, mainly because of the cross-sectional area of the equator is highest. The same time, the fracture strength of the eggshell was bigger than the whole egg. The results also show that the fracture strength were highly dependent on the loading direction and its rate (p<0.01).

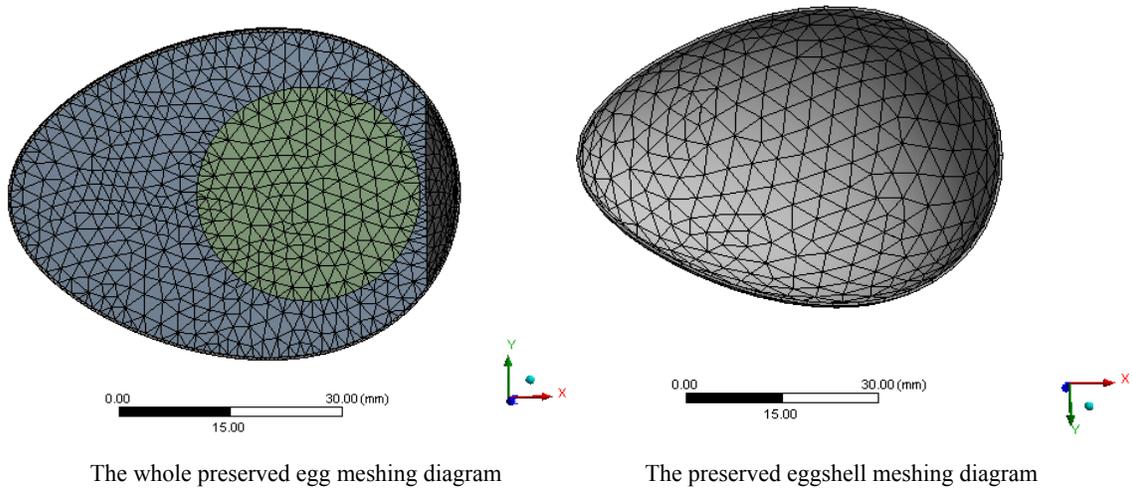
The biggest fracture strength range of whole egg and egg shell when loading by the cup direction as followed: the whole egg was 48.6~30.8 N, egg shell was 51.0~28.7 N. The second was blunt end: the whole egg was 31.4~43.1 N, egg shell was 20.1~41.3 N. The third was equator: the whole egg was 22.6~30.8 N, It maybe because the resistance of preserved egg's material structure on the equator was lower than other directions. For all curves, it needs the biggest fracture strength when loading into the lowest compression rate. It mainly depended on each preserved egg's physical property of its fracture strength. For example, surface area, cross-sectional area, shell thickness, etc. In this study, the scope of preserved egg sectional area was from 6496.3 to 6870.8 mm<sup>2</sup>, the scope of its cross-sectional area was from 2172.3 to 2294.3 mm<sup>2</sup>, the scope of its shell thickness was from 0.46 to 0.51 mm.

**Unit deformation:** The unit deformation with the change of loading rate and the direction of whole egg and egg shell in Fig. 5. With the increasing of compression rate, the range of whole egg's unit deformation was from 1.24 to 3.78%, the range of egg shell's unit deformation was from 1.5 to 4.25%. The results showed that unit deformation were highly dependent on compression rate and its loading direction (p<0.01). In general, with the change of the loaded object and loading rate increasing, the unit deformation were increased. The smallest was the blunt and the equator was the largest.

The range of unit deformation by whole egg and egg shell when loading along the cup direction as followed: the whole egg was from 1.60 to 3.61%, the egg shell was from 1.4 to 2.84%. The range along the blunt end as followed: the whole egg was from 1.24 to 3.27%, the egg shell was from 1.10 to 2.45%. This may because the cross-sectional area of preserved egg's cup was the smallest, leading their fracture resistance and unit deformation is higher than the blunt end's. The range of unit deformation by whole egg and egg shell when loading along the equator direction as followed: the whole egg was from 1.78 to 4.91%, the egg shell was from 1.6 to 4.25%. This may because the cross-sectional area and fracture resistance of equator was stronger than other two direction.

**Energy:** The fracture energy with the change of loading rate and the direction of whole egg and egg shell in Fig. 6. It showed that fracture energy of the whole egg and egg shell was highly dependent on compression rate and its loading direction (p<0.01). As the change of loading rate, the range of their fracture energy were as followed: the whole egg was from 6.03 to 12.32 mJ, egg shell was from 5.67 to 13.63 mJ. In general, as loading rate increased, the fracture energy was also gradually increased of its loading direction. What's more, It followed the rule the cup was the largest, blunt end was lager and the equator was smallest. This may be related to the cross-sectional area in different structure of preserved egg.

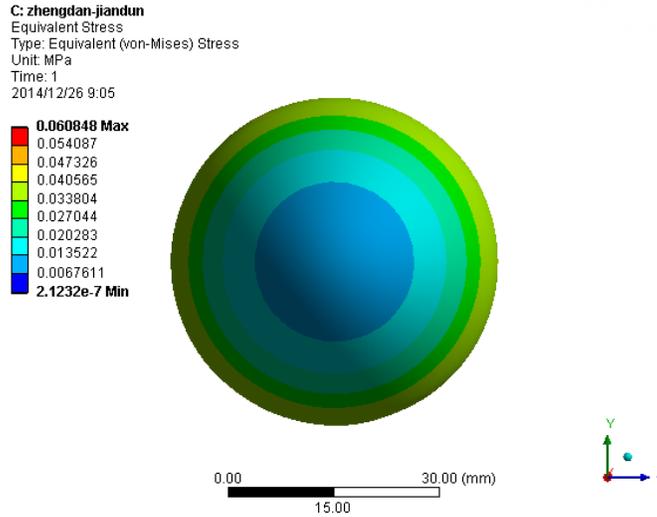
The range of their fracture energy when loading along the cup were as followed: the whole egg was from 7.89 to 11.49 mJ, egg shell was from 8.90 to 13.63 mJ. Along the blunt end were as followed: the whole egg was from 6.03 to 11.48 mJ, egg shell was from 7.51 to 11.95 mJ. Along the equator were as followed: the whole egg was from 8.20 to 12.32 mJ, egg shell was from 6.03 to 8.80 mJ.



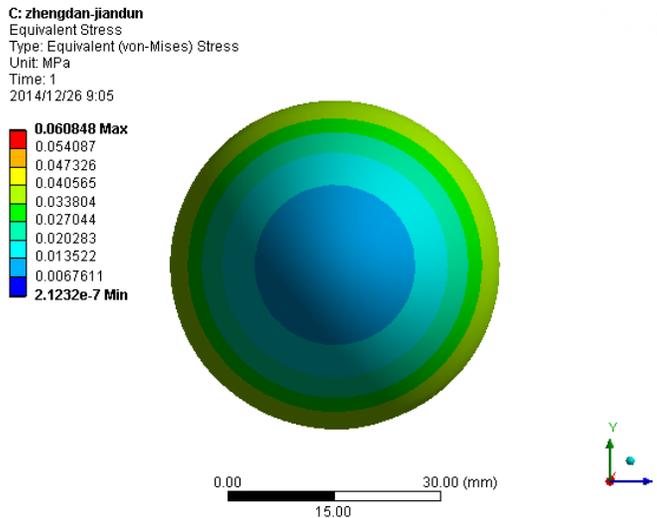
The whole preserved egg meshing diagram

The preserved eggshell meshing diagram

Fig. 7: Preserved egg each structure finite element mesh division

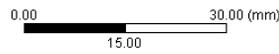
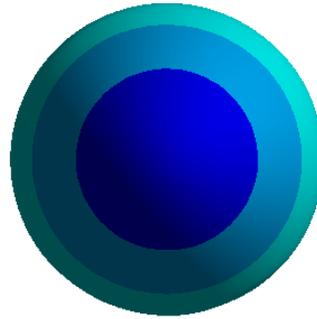
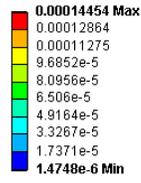


(a) Tip-displacement graph of the whole egg



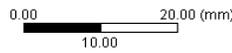
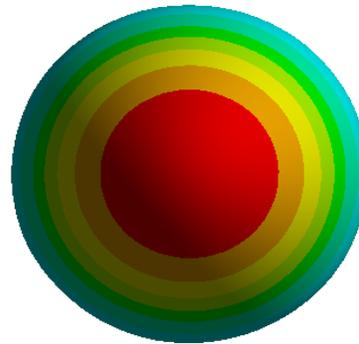
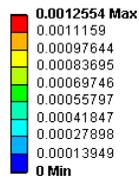
(b) Tip-stress graph of the whole egg

C: zhengdan-jiandun  
Equivalent Elastic Strain  
Type: Equivalent Elastic Strain  
Unit: mm/mm  
Time: 1  
2014/12/26 9:05



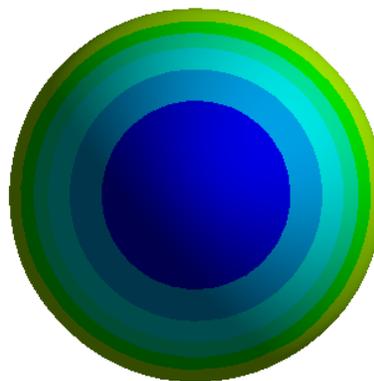
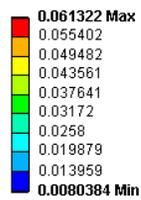
(c) Tip-strain graph of the whole egg

C: danke-jianduan  
Total Deformation  
Type: Total Deformation  
Unit: mm  
Time: 1  
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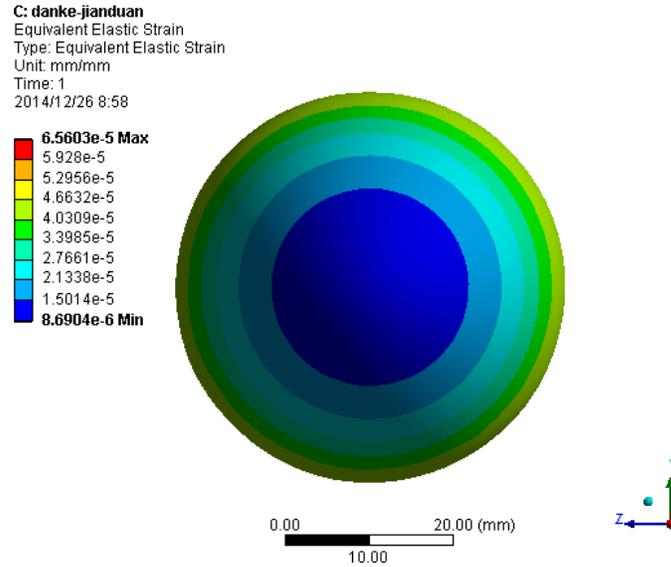


(d) Tip-displacement graph of the eggshell

C: danke-jianduan  
Equivalent Stress  
Type: Equivalent (von-Mises) Stress  
Unit: MPa  
Time: 1  
2014/12/26 8:58



(e) Tip-stress graph of the eggshell



(f) Tip-strain graph of the eggshell

Fig. 8: Preserved egg after the tip of each structure under load stress and strain contours

### THE FINITE ELEMENT ANALYSIS OF THREE DIFFERENT STRUCTURAL MECHANICS CHARACTERISTICS OF PRESERVED EGG

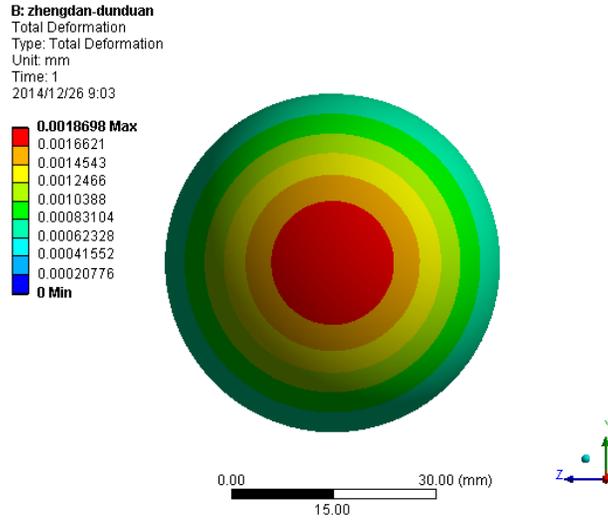
Applying ANSYS-Workbench method analyzes compression mechanical properties of each structure of preserved egg. First of all, establishing its finite element model and then use the finite element analysis (Zhang *et al.*, 2008; Wang, 2013; Chen *et al.*, 2011).

**Structural model:** Preserved egg consists of eggshell, egg white and egg yolk with solid state. The mainly factor affects the mechanical properties was eggshell, solid-state egg white and egg yolk. Therefore, we divide into three parts to establish its finite element model. Selecting frictionless contact way among each part, defining eggshell is brittle material, the other is defined linear elastic material. The preserved egg geometry size is measured by experiment: long axis is 60.00 ( $\pm 0.50$ ) mm, short shaft is 45.00( $\pm 0.50$ ) mm, average eggshell thickness is 0.485 mm, average egg white diameter is 30.00 mm.

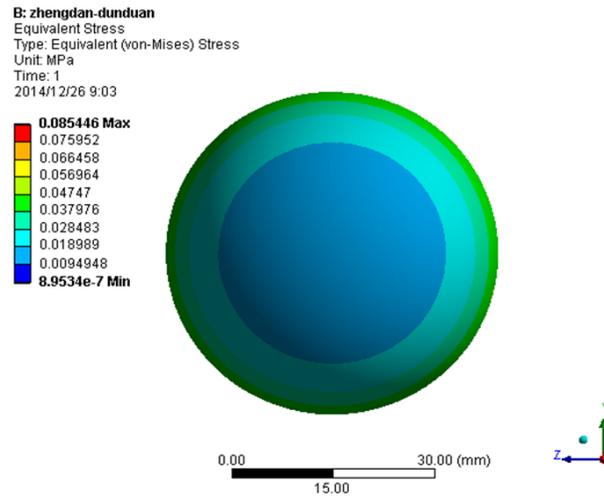
**The grid division and load:** When establishing finite element model, we select Auto mesh method and Relevance for 100 to mesh each structure. The modulus of elasticity of eggshell was obtained by the experiment: loading on middle is 3.355 MPa, loading on both ends is 3.357 MPa, solid elastic modulus of egg white and egg yolk is 0.1440 MPa. Poisson's ratio is 0.2. The mesh model and the load model (Fig. 7a and b), practicing the area constraints when loading at the bottom surface and concentrated load is applied at the top.

**Finite element simulation of preserved egg compression force- deformation curve:** Simulation the whole egg and eggshell, respectively, in different loading direction of cutting-edge, blunt end and equator. Thus, we can read the clouds of the distribution of stress and strain state:

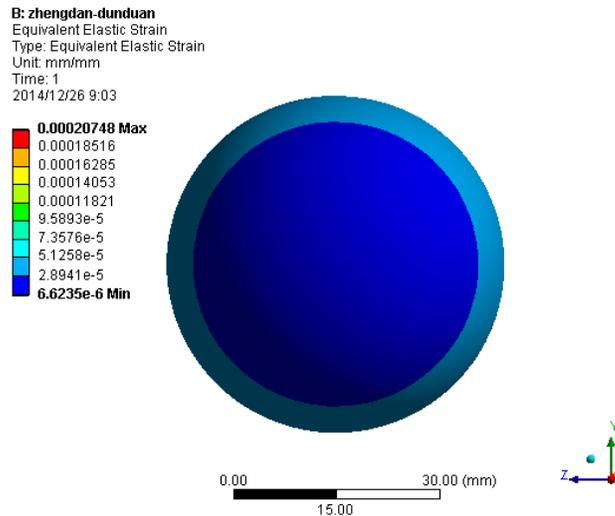
- A concentrated load was applied on the tip of the whole eggs and egg shell (Fig. 2a), According to the test result, the concentrated load size was 45 N. It was showed that the stress and strain of each structural could present certain characteristics as follow (Fig. 8).
- The maximum stress and strain was appeared on the top of the surface, namely the position of the applied load. At the same time, it was the first broken position of each structure and consistent with the experimental results, the stress and strain gradually decrease from all around until the minimum.
- Because the bottom of each structure is flat, namely the position of the fixed constraints imposed, the stress and strain produced was minimal.
- A concentrated load was applied on the blunt end of the whole eggs and egg shell (Fig. 2c), According to the test result, the concentrated load size was 25 N. It was showed that the stress and strain of each structural could present certain characteristics as follow (Fig. 9a to c). The stress of each structure had a wide distribution range across the bottom edge. Because of the concentrated load, the region produce larger stress and to extend. The first broken position was blunt end of preserved egg where the load was applied.



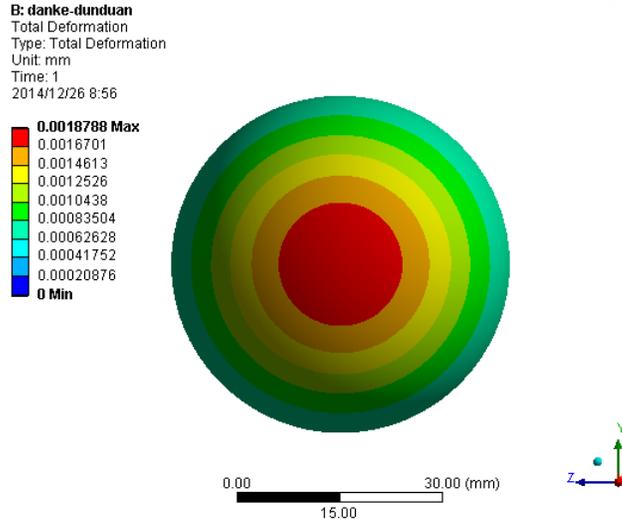
(a) Blunt-displacement graph of the whole egg



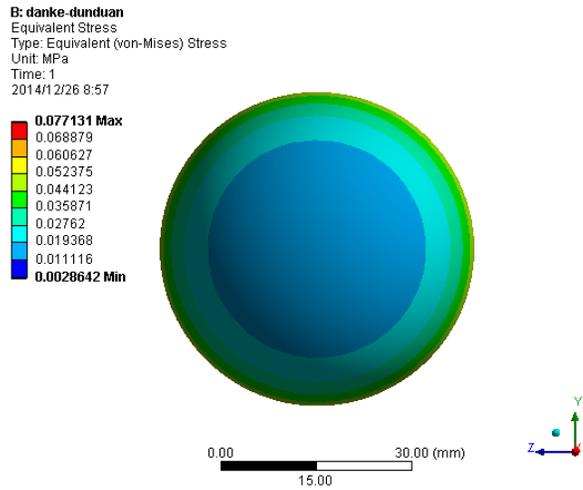
(b) Blunt-stress graph of the whole egg



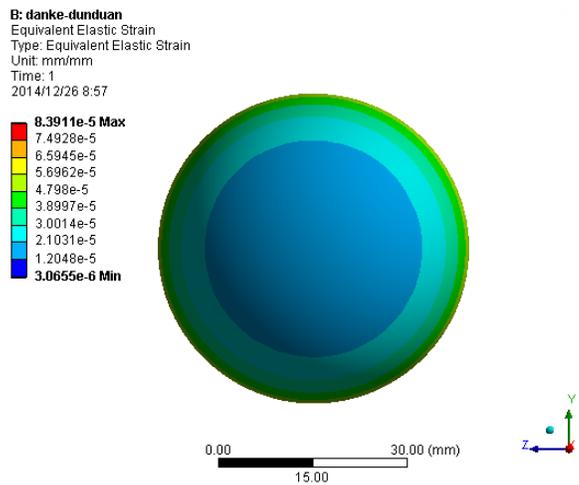
(c) Blunt-strain graph of the whole egg



(d) Blunt-displacement graph of the eggshell

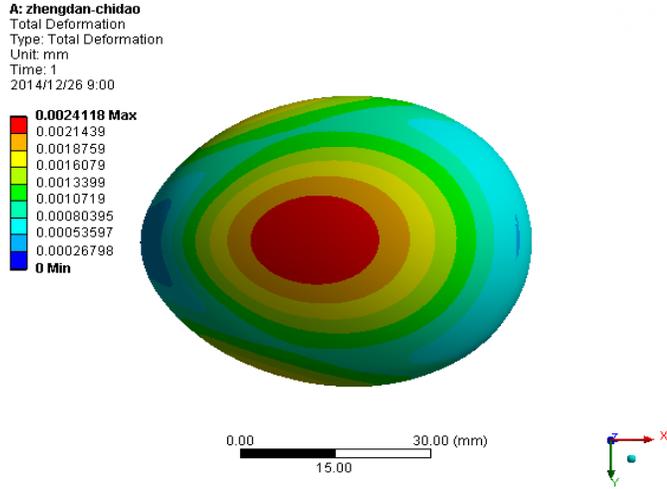


(e) Blunt-stress graph of the eggshell

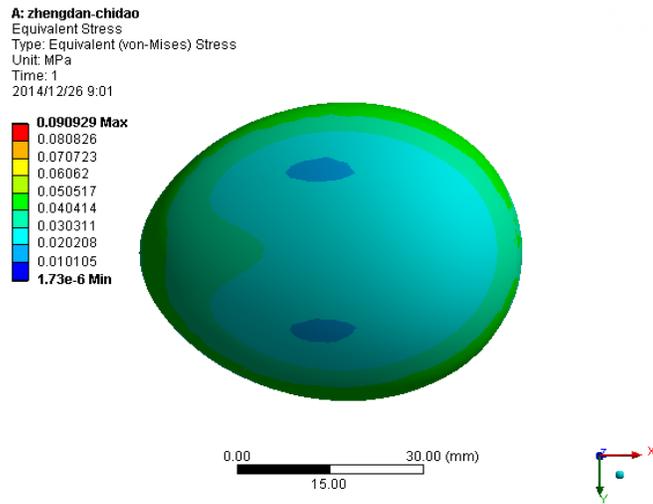


(f) Blunt-strain graph of the eggshell

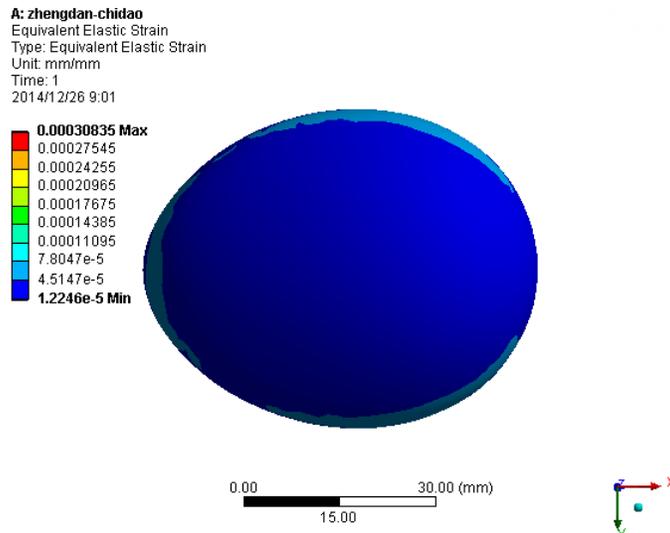
Fig. 9: Preserved egg after blunt end of each structure under load stress and strain contours



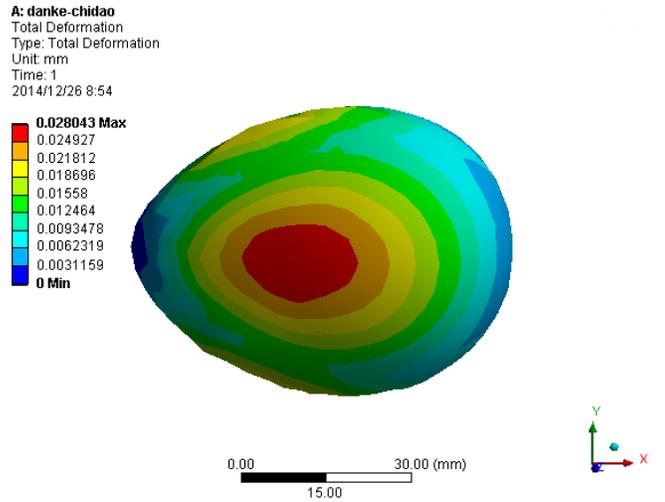
(a) Equator-displacement graph of the whole egg



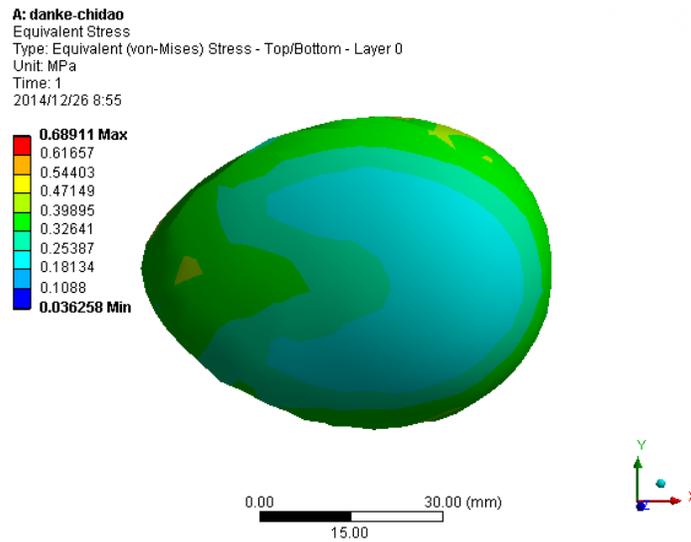
(b) Equator-stress graph of the whole egg



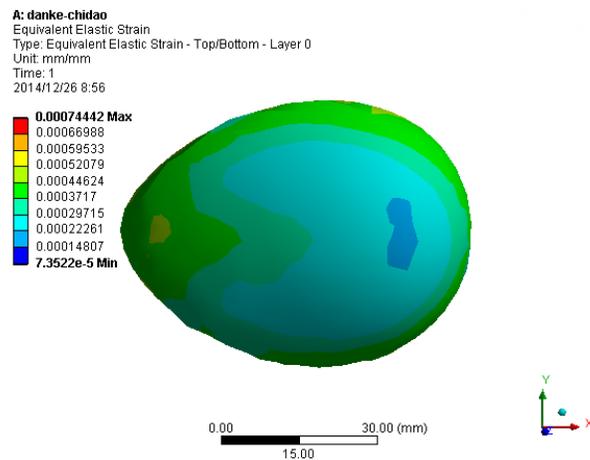
(c) Equator-strain graph of the whole egg



(d) Equator-displacement graph of the eggshell



(e) Equator-stress graph of the eggshell



(f) Equator-strain graph of the eggshell

Fig. 10: Preserved egg equator after loading stress and strain contours of each structure

The distribution of nodes equivalent strain of each structure (Fig. 9c) showed that the strain of each preserved egg structure was mainly existed in the area and the surrounding the load concentrated. Above all, the maximum strain appeared in concentrated load and this result consistent with the distribution of the stress (Fig. 9d to f).

- A concentrated load was applied on the equator of the whole eggs and egg shell (Fig. 2b), According to the test result, the concentrated load size was 22.5 N. It was showed that the stress and strain of each structural could present certain characteristics as follow (Fig. 10a to c). The stress of each structure had a wide distribution range across the bottom edge. Because of the concentrated load, the region produce larger stress and to extend. The first broken position was equator of preserved egg where the load was applied.

The distribution of nodes equivalent strain of each structure (Fig. 10b to d) showed that the strain of each preserved egg structure was mainly existed in the area and the surrounding the load concentrated. Above all, the maximum strain appeared in concentrated load and this result consistent with the distribution of the stress (Fig. 10e and f).

### CONCLUSION

- Linear correlation of the physical properties of preserved egg's appearance. The linear relationship among the surface area (Sa), cross-sectional area (Sc), volume (V) and perimeter (L) of preserved egg are as follow:  $V = 9.62 S_a$ ,  $V = 28.79 S_c$ ,  $V = 411.74 L$ . The variance are as follow:  $S(V, S_a) = 17.44$ ,  $S(V, S_c) = 53.18$ ,  $S(V, L) = 1228.55$ .
- It shows that the structure and mechanical properties of preserved egg conform to the laws of the anisotropic through the damage mechanism of the test and the finite element simulation analysis. Including compression fracture force on both ends, the unit deformation and fracture energy were greater than the middle pressure corresponding characteristic; And under the same pressure in both directions stress direction is greater than the equator, strain instead.
- Mechanical properties of preserved egg's each structural presents ladder type changes. In the same loading direction, the fracture strength, unit deformation and fracture energy of the whole egg is stronger than egg shell. At different loading rates and loading direction, It also has different mechanical properties:

- At different rate and in the same loading direction, the results decreases when the loading rate increasing.
- At the same rate, in different loading direction, the results follow the rule the cup's mechanical properties is the strongest, the equation is the weakest.
- The finite element simulation analysis results show that this model can analysis the mechanical properties of preserved egg. The results shows: stress and strain are to gradually change from loading to the bottom and the most significant of the loading point.
- Future research and discussion. Through the results about breakage mechanism of preserved egg, it is need to further research How to change the packing materials and the way to reduce the damage in other link.

### ACKNOWLEDGMENT

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