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Influence of hen egg shape on eggshell compressive strength**

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Abstract. Eggshell behaviour at static compression was investigated. Exact description of the eggshell contour shape was used for verification of a commonly accepted theory on the compression of bodies of convex form. Particularly, the shape of the eggshell contour was described using polar coordinates r, φ, and radius of the curvature, R. Two compression axes were used to determine the rupture force, specific deformation, rupture energy and firmness. Energy absorbed by an egg at the moment of rupture was also determined. The least resistance to rupture was observed for eggs compressed between the poles. Also other quantities connected with the eggshell damage depend on the orientation of the loading force during egg compression. It was found that egg shape influenced the energy absorbed during egg loading, both in the pole and the equator planes. The other parameters were not affected by egg shape. The experiments revealed that the deformation behaviour of the eggshell was elastic. Elastic constants (39.9±8.5 GPa) and (0.345) were calculated. Two different methods were used and results of both procedures were nearly the same. Elastic constants were independent on the egg shape as well as on the loading force orientation. Presented numerical simulation of the experiments gave more detailed information on the stress state in the loaded eggshell. LS DYNA 3D finite element code was used for the simulation.

Keywords: eggshell shape index, strength, elasticity, eggshell stiffness, numerical simulation

INTRODUCTION

The function of the eggshell is to protect the contents of the egg from mechanical impacts and microbial invasion *eg Salmonella* attack, and to control the exchange of water and gases through the pores. A commonly used technique for the measurement of the shell strength is the quasi-static compression of an egg between two parallel steel plates (Coucke *et al.*, 1998; De Ketelaere *et al.*, 2002).

Eggshell strength is affected by many factors like the microstructure, and thickness of eggshell, loading rate, specific gravity, mass, volume, surface area, shell percentage of egg *etc*. One of these factors is the egg shape. The influence of the eggshell shape on its mechanical properties has been studied in many papers (Anderson *et al.*, 2004). The eggshell shape has been described using of the shape index (*SI*) which is defined as:

$$SI = \frac{W}{L}100, \qquad (1)$$

where: W is the width and L the length of the egg. Eggs are characterised by the *SI* as sharp, normal (standard) and round if they have an *SI* value of <72, between 72 and 76, and >76, respectively (Sarica and Erensayin, 2004). Even if this parameter is very convenient (Altuntaş and Şekeroğlu, 2008) for details, a more exact description of the eggshell shape is sometimes needed. The exact description of the eggshell shape can be obtained mostly by using digital image analysis of the eggs. This procedure is briefly described in the following section. The influence of the eggshell shape on the mechanical behaviour of eggs was studied using the compression test mentioned above. The stress distribution in the eggshell during these experiments was evaluated using an adequate numerical method.

The aim of this study was to determine the impact of the eggshell shape on the stress at which the eggshell breaks. Unlike in the work of above mentioned authors, the exact description of eggshell shape was used in this work. Instead of fracture force, stress in the eggshell was used for the evaluation of eggshell strength.

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EVALUATION OF EGG SHAPE

There are many experimental methods of eggshell shape determination. A more detailed survey can be found (Havlíček *et al.*, 2008). The simplest method consists in the evaluation of the shape index *SI* – see previous chapter. A more exact description of the eggshell contour has been developed in Narushin (2001):

$$y=\pm\sqrt{L^{\frac{2}{n+1}}x^{\frac{2n}{n+1}}-x^2}$$

$$n=1.057\left(\frac{L}{W}\right)^{2.372}, \qquad (2)$$

where: x is the coordinate along the longitudinal axis and y – the transverse distance to the profile. A more accurate description of the egg shape can be obtained from digital photographs. The application requires one measured dimension (the egg length, measured with sliding calliper), and allows the user to determine any user defined distance on the photograph from the derived number of pixels per unit length. From the dimensional measures of individual eggs, their contours can be accurately described in a user defined Cartesian coordinate system, using a mathematical equation (Carter, 1974). For more details, the reader is referred to the procedure described by Denys *et al.* (2003). Three dimensional egg shapes can be then obtained by revolving the contours 180° about the axis of symmetry. The shape of the eggshell contour can be described using of the polar coordinates r, φ as:

$$x=r\cos\varphi \qquad y=r\sin\varphi,$$

where:

$$r(\varphi)=a_o+\sum_{i=0}^{\infty}\left(a_i\cos\left(2\pi\frac{\varphi}{c_i}\right)+b_i\sin\left(2\pi\frac{\varphi}{c_i}\right)\right), \qquad (3)$$

and a_i, b_i, c_i are Fourier coefficients which must be determined from the digital image.

The analysis of our data led to the conclusion that the first five coefficients of the Fourier series are quite sufficient for the egg contour shape description (the correlation coefficient between measured and computed egg profiles lies between 0.98 and 1). In Fig. 1 an example of egg contours computed using Eq. (2) and determined from the digital photography is displayed. One can see that there is some difference between these two contours. Knowledge of the equation describing the eggshell contour is necessary namely for the numerical simulation of egg behaviour under different mechanical loading, at numerical simulation of different heat treatment, and also for the determination of the curvature of this curve. The radius of the curvature, R, then plays a meaning role at the evaluation of some egg loading tests (compression test, *etc.*) (MacLeod *et al.*, 2006). This radius can be solved by the following system of equations:

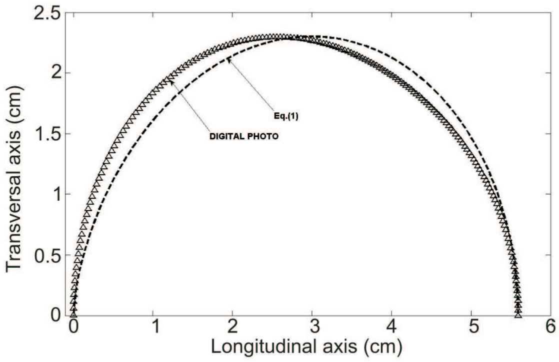

Fig. 1. Comparison of two methods of eggshell contour evaluation.

$$F(\varphi)=(x-x_o)^2+(y-y_o)^2-R^2$$

$$F(\varphi)=0$$

$$\frac{dF(\varphi)}{d\varphi}=0$$

$$\frac{d^2F(\varphi)}{d\varphi^2}=0, \qquad (4)$$

where: x_0, y_0 are the coordinates of the centre of curvature of a given curve. If the curve is described as function $y=f(x)$ – then the radius of the curvature is given as:

$$R=\frac{\left(1+\left(\frac{dy}{dx}\right)^2\right)^{\frac{3}{2}}}{\frac{d^2y}{dx^2}}. \qquad (5)$$

MATERIAL AND EXPERIMENTAL METHODS

Eggs (Hisex Brown strain) were collected from a commercial packing station. Typically, the eggs were maximally 2 days old when they arrived at the packing station. The main characteristics of the eggs were evaluated: mass, eggshell thickness, egg length (L) and egg width (W). The shapes most often encountered are sharp, normal (standard), and round eggs which are enumerated on the *SI* scale as <72, 72-76, and >76, respectively. The description of the eggshell contour shape was performed using the procedure mentioned in the previous chapter. A total sample of 120 eggs were used. The eggs were compressed between two plates using the testing device TIRATEST. The egg sample was placed on the fixed plate and loaded at the compression speed of 0.33 mm s^{-1} and pressed with a moving plate connected to the load cell until the egg ruptured.

Two compression axes of an egg, as shown in Fig. 2, egg were used to determine the rupture force, specific deformation, rupture energy and firmness.

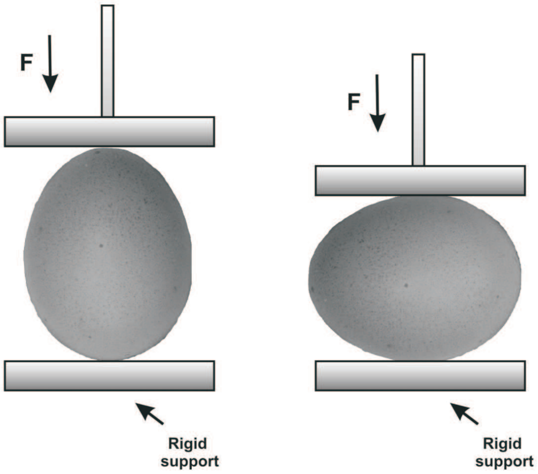

Fig. 2. Schematic of egg loading.

The main geometric characteristics of eggs used for the experiments are given in Tables 1 and 2. The distribution of the eggs according to their shape is shown in Figs 3 and 4. One can see that most of the eggs can be considered as normal or round, respectively.

The specific deformation was obtained from the following equation:

$$\varepsilon = \left(1 - \frac{L_f}{L}\right)100, \tag{6}$$

where: L (mm) is the undeformed egg length measured in the direction of the compression axis and L_f (mm) is the deformed egg length measured in the direction of the compression axis (Braga *et al.*, 1999).

Energy absorbed (E_a) by an egg at the moment of rupture was determined by calculating the area under the force-deformation curve from the following equation:

$$E_a = \frac{F_r D_r}{2}, \tag{7}$$

where: F_r is the rupture force and D_r is the eggshell displacement at the point of rupture on the egg.

Firmness is regarded as a ratio of compressive force to displacement at the rupture point of an egg. The firmness was obtained from the following equation:

$$Q = \frac{F_r}{D_r} \; . \tag{8}$$

RESULTS AND DISCUSSION

An example of the experimental record of force vs. egg displacement is shown in Fig. 5. The same qualitative features were exhibited by all tested eggs. The force linearly increased with the egg displacement, followed by a sudden drop to zero. The linear fit of the force-displacement points is very good. The correlation coefficient is better than 0.985. It was assumed that rupture occurred at the bioyield point

Table 1. Selected physical and geometric properties of eggs tested in the equator plane

Shape index	Value	Mass (g)	Length (mm)	Width (mm)	Shape index (%)
SI<72	Max	79.06	66.51	46.50	71.62
	Min	68.03	61.74	44.22	69.91
	Mean	73.55	64.13	45.36	7.77
	SD	3.51	1.28	0.81	0.84
72<*SI*<76	Max	75.75	62.45	46.32	76.98
	Min	55.53	55.53	42.15	72.12
	Mean	66.33	59.75	44.40	74.29
	SD	5.59	1.99	1.17	1.45
SI>76	Max	77.44	61.35	47.43	83.58
	Min	55.25	54.39	43.07	76.06
	Mean	66.14	57.74	45.17	78.33
	SD	5.26	1.66	1.23	1.97

SD – standard deviation.

Table 2. Selected physical and geometric properties of eggs loaded between poles

Shape index		Mass (g)	Length (mm)	Width (mm)	Shape index (%)
SI<72	Max	69.27	62.20	44.55	71.62
	Min	59.41	60.47	43.44	71.81
	Mean	64.27	61.02	43.01	70.59
	SD	3.49	0.70	41.77	69.08
72<*SI*<76	Max	75.37	62.30	44.55	75.66
	Min	57.78	56.50	41.77	72.05
	Mean	65.13	59.51	43.19	74.08
	SD	4.23	1.59	1.00	1.15
SI>76	Max	77.09	60.51	47.68	83.94
	Min	57.45	53.12	42.86	76.15
	Mean	65.54	57.56	44.96	78.13
	SD	4.83	1.60	1.201	1.81

Explanations as in Table 1.

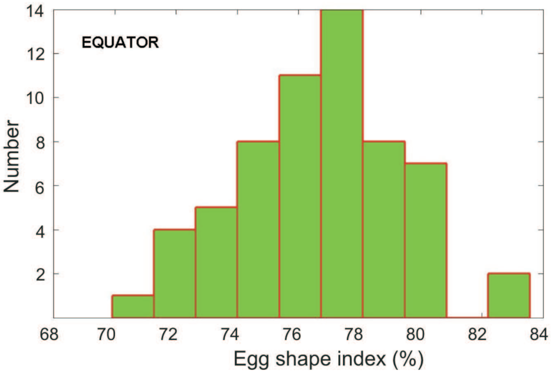

Fig. 3. Histogram of *SI* values. Loading in the equator plane.

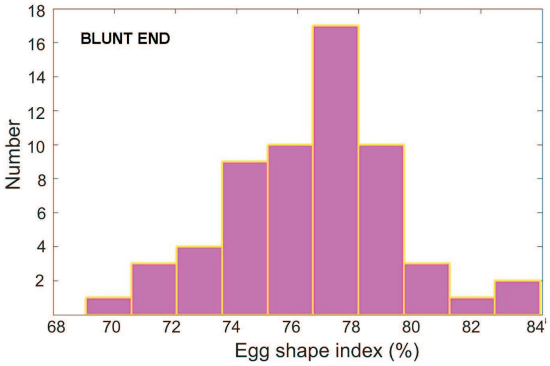

Fig. 4. Histogram of *SI* values. Eggs loaded between the poles.

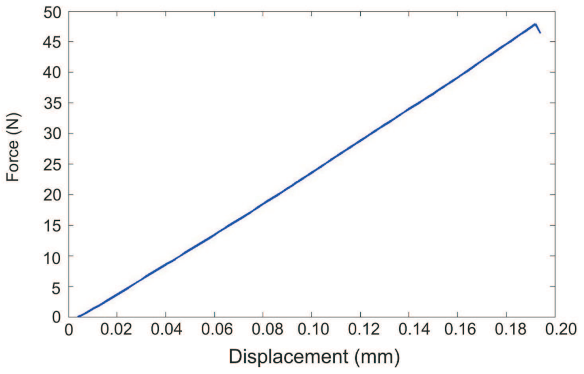

Fig. 5. Example of experimental record of compressive force-displacement. Egg loaded in the equator plane.

which is the point on the force-deformation curve at which there was a sudden decrease in force. The distribution of the rupture forces obtained for two loading orientations is shown in Fig. 6a, b. The mean values of the measured egg characteristics together with some statistics are given in Tables 3 and 4.

The least resistance to rupture was observed for the eggs compressed between the poles. During this loading all measured eggshell characteristics were lower than those obtained for loading in the equator plane. The only exception was in the values of firmness. These conclusions are in disagreement with the results presented by Altuntas and Şekeroğlu (2008). Those authors also found that the rupture force depends on the egg shape. In Figs 7-11 the average values of rupture force, displacement, strain, energy and firmness are displayed. The dependence of the rupture force on the egg shape can be observed only for eggs compressed in the equator plane. There is a question if the data obtained for the sharp shape ($SI < 72$) may be considered with respect to their small number. The egg shape exhibits an effect on the energy absorbed during the egg loading. This influence is also confirmed for eggs loaded in the equator plane. The

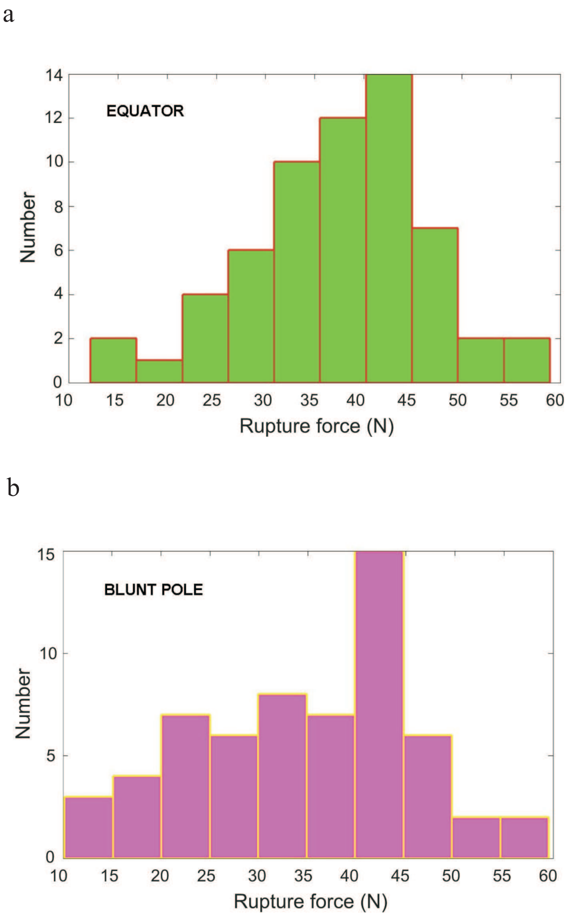

Fig. 6. Histogram of rupture force: a – eggs loaded in the equator plane, b – eggs compressed between the poles.

Table 3. Eggs loaded in the equator plane

Value	Shape index (%)	Rupture force (N)	Displacement (mm)	Strain (%)	Energy (N mm^{-1})	Firmness (N mm^{-1})
Max	83.58	58.96	0.61	1.07	11.17	368.50
Min	69.91	10.03	0.10	0.17	1.22	27.62
Mean	73.77	36.43	0.28	0.48	5.10	158.59
SD	14.34	11.25	0.13	0.23	2.60	80.37

Table 4. Eggs compressed between the poles

Value	Shape index (%)	Rupture force (N)	Displacement (mm)	Strain (%)	Energy (N mm^{-1})	Firmness (N mm^{-1})
Max	83.94	59.59	0.47	0.78	9.01	767.67
Min	69.08	10.20	0.06	0.003	0.53	52.94
Mean	76.47	34.92	0.16	0.27	2.80	269.90
SD	3.12	12.02	0.09	0.15	1.79	151.31

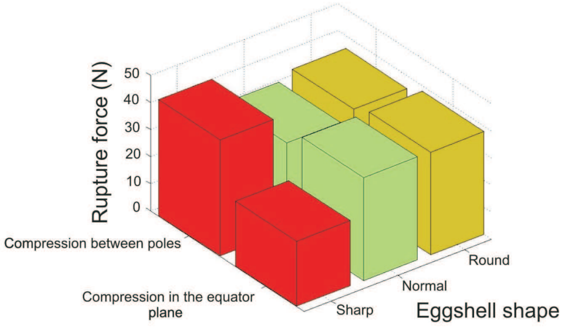

Fig. 7. Average values of rupture force for different loading orientations and egg shapes.

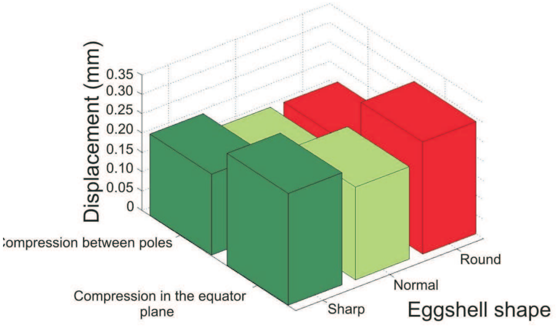

Fig. 8. Average values of displacement at egg rupture for different loading orientations and egg shapes.

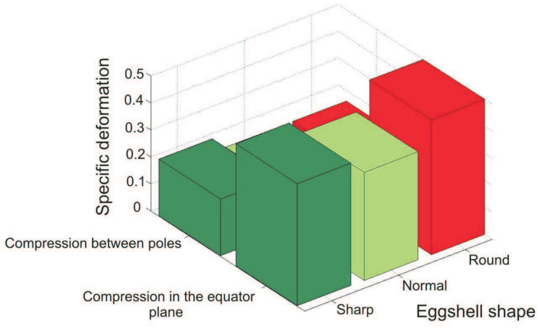

Fig. 9. Average values of deformation at egg rupture for different loading orientations and egg shapes.

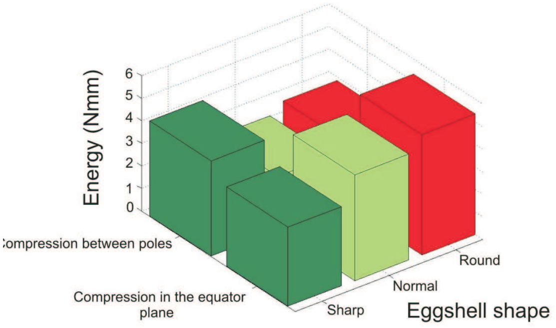

Fig. 10. Average values of energy absorbed by eggshell during its deformation.

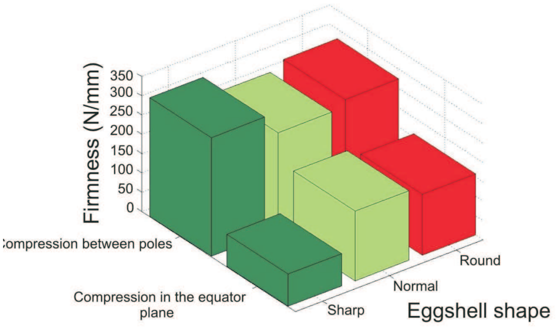

Fig. 11. Influence of egg shape on firmness.

remaining parameters are not affected by the egg shape. This conclusion is in discrepancy with the findings presented by Altuntaş and Şekeroğlu (2008). It is obvious that some additional experiments are urgently needed.

The experiments revealed that the deformation behaviour of the eggshell was elastic. If we consider the elastic strain as isotropic and linear, the elastic properties are described by the Young modulus, *E*, and by the Poisson ratio, ν. Buchar *et al*. (2002) developed an experimental method of the evaluation of these elastic constants. In their method a strain gauge rosette is mounted on the egg surface. The strain gauge enables to measure the relationship between the applied load and the local meridian and hoop strains. This procedure thus gives two equations which could be solved simultaneously.

Another method for compression tests of food materials of convex shape is described in ASAE (2001). The modulus of elasticity is evaluated from the following equation:

$$E = \frac{0.531F\left(1-\nu^2\right)}{x^{\frac{3}{2}}}\left[2\left(\frac{1}{R}+\frac{1}{r}\right)^{\frac{1}{3}}\right]^{\frac{3}{2}}.$$

The meaning of radius *R* and *r* is illustrated in Fig. 12. The use of the experimental method mentioned above gives the following values of the elastic constants: E= 39.9±8.5 GPa, γ = 0.345. Keeping ν constant, the use in previous equation leads to E = 38.7±14.3 GPa. The computation was performed for the force F =5 N and corresponding displacement x. The force is significantly lower than the rupture force. Owing to the linear dependence *F*=*F*(*x*), the corresponding displacement is also lower than that at the rupture point. It means the radius of the curvature, *R*, *r*, obtained for the undeformed egg can be used. The value of *E* is independent from the loading orientation. This dependence has been found in McLeod *et al.* (2006). Those authors, of course, used another type of the equation. The found values of the elastic constants can be used for the numerical simulation of our experiments.

NUMERICAL SIMULATION

For the numerical simulation of the experiments described in the previous chapters, the LS DYNA 3D finite element code was used. As a first step the finite element model of the egg was developed. The model is based on the following assumptions:

- eggshell is a homogeneous isotropic linear elastic material, the properties of such material are described by the Young modulus, Poisson ratio and material density;
- membranes are also taken as linear elastic material, no difference between membranes was considered;
- air is considered as an ideal gas;
- egg yolk as well as egg white are considered as compressible liquids.

The elastic properties of the eggshell are calculated by use of equation given in previous chapter. The density of the eggshell was determined as 2.14 g cm^{-3}. Elastic properties of the membranes were determined by the method described in Ju *et al.* (2002). The density of the membranes was determined as 1.01 g cm^{-3}, E = 0.0035 GPa, and ν = 0.45. The properties of the egg liquids are given in Table 5.

The numerical model is shown in Fig. 13. The plate is considered as rigid.

The shell elements were used. It means the computation enables to obtain normal stresses in the *x* and *y* directions, σ_{xx}, σ_{yy}, and shear stress, σ_{xy}. These stresses were evaluated at the inner and outer surfaces of the eggshell. These three stresses can be substituted by the von Mises (effective) stress which is defined as:

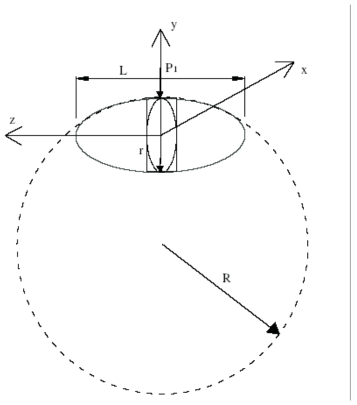

Fig. 12. Radius of curvature of eggshell curve.

Table 5. Properties of the egg liquids (*K* – bulk modulus)

Egg liquid	ρ (g cm^{-3})	*K* (GPa)
White	2.14	2.0
Yolk	1.01	1.8

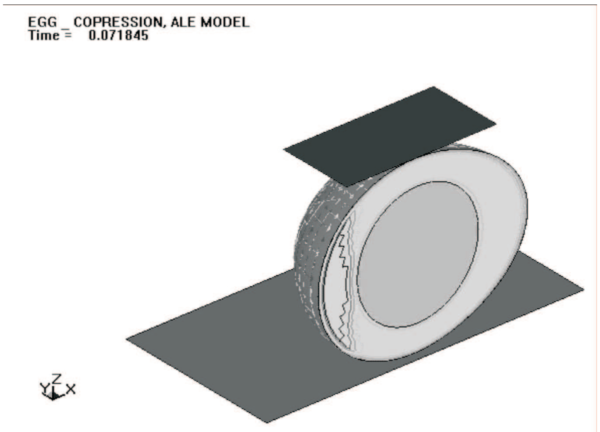

Fig. 13. Numerical model of egg compression. Owing to symmetry only one half of the egg is considered.

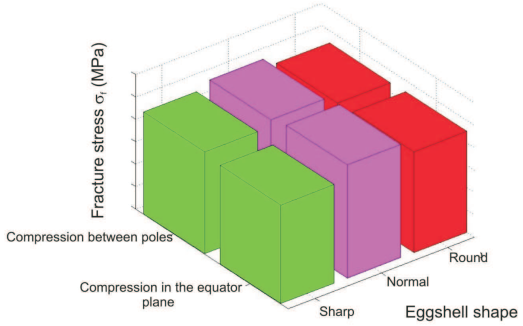

Fig. 15. Fracture stress of tested eggs. Stress was evaluated at about 2 mm from the point of contact between the egg and the plate.

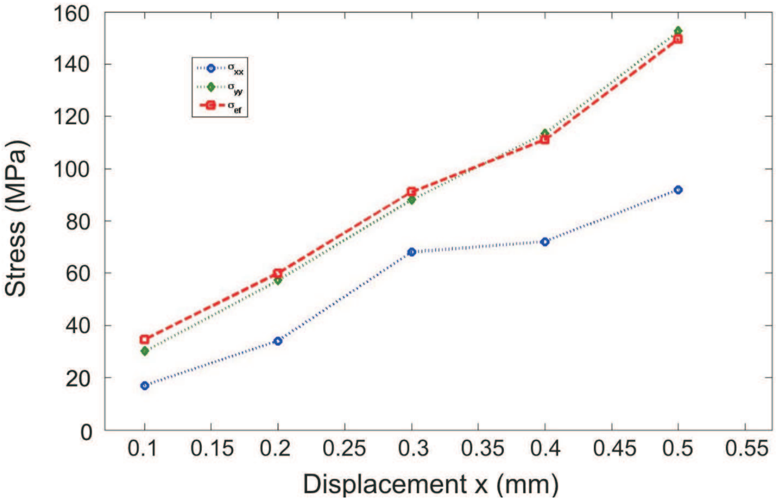

Fig. 14. Example of stress components as function of egg displacement during its compression.

Table 6. Fracture stress of tested eggs

Egg shape	Pole loading	Equator loading
	σ_f (MPa)	
Sharp	91	88
Normal	97	101
Round	89	90

$$\sigma_{ef} = \sqrt{2\sigma^2_{xx} + 2\sigma^2_{yy} - 2\sigma_{xx}\sigma_{yy} + 6\sigma^2_{xy}} \; .$$

These stresses were computed for different values of eggshell displacement. An example of this computation is shown in Fig. 14. These dependences were used for the evaluation of the von Mises stress at displacement corresponding to the egg fracture. This stress can be taken as the fracture stress σ_f. Its values are given in Table 6. The results are plotted in Fig. 15. One can see that the fracture stress probably does not depend on the eggshell shape nor on the orientation of the loading force. This stress is a promising candidate as a quantity affected only by the material properties of the eggshell. Verification of this hypothesis must be the subject of some other research projects.

CONCLUSIONS

1. Results obtained in the given paper suggest that the rupture force of the eggshell and other quantities connected with the eggshell damage (displacement at the eggshell rupture, specific deformation, energy absorbed during deformation and firmness) depends on the orientation of the loading force during eggs compression. Contrary to the results of another works there is not too significant dependence of these parameters on the egg's shape.

2. The values of the elastic constants describing the strain behaviour of the eggs have been found. Two independent methods have been used. Results of the both procedures are nearly the same. Elastic constants are independent on the egg shape as well as on the loading force orientation. The use one of the used methods was conditioned by the exact description of the eggshell contour. The description of this curve has been also used for the numerical simulation of the eggs compression.

3. Preliminary results suggest that there is a stress at which the eggshell rupture starts. This stress is very probably independent on the eggshell geometry, egg's size, eggshell thickness and on the loading force orientation. This stress can be used as the fracture stress which is affected only by the eggshell material properties. The verification of this hypothesis will be subject of the forthcomming paper.

REFERENCES

Altuntaş E. and Şekeroğlu A., 2008. Effect of egg shape index on mechanical properties of chicken eggs. J. Food Eng., 85, 606-612.

Anderson K.E., Tharrington J.B., Curtis P.A., and Jones F.T., 2004. Shell characteristics of eggs from historic strains of Single Comb White Leghorn chickens and the relationship of egg shape to shell strength. Int. J. Poultry Sci., 3, 17-19.

ASAE, S368.4, **2001.** Compression Test of Food Materials of Convex Shape. ASAE Press, St. Joseph, MI, USA.

Braga G.C., Couto S.M., Hara T., and Almeida Neto J.T.P., 1999. Mechanical behaviour of macadamia nut under compression loading. J. Agric. Eng. Res., 72, 239-245.

Buchar J. and Simeonovova J., 2001. On the identification of the eggshell elastic properties under quasistatic compression. Proc. 19th CAD – FEM Users Meeting, Int. Cong. FEM Technology, October 17-19, Potsdam-Berlin, Germany.

Carter T.C., 1974. The hen's egg: estimation of shell superficial area and egg volume from four shell measurements. British Poultry Sci., 15, 507-511.

Coucke P., Jacobs G., Sas P., and De Baerdemaeker J., 1998. Comparative analysis of the static and dynamic mechanical eggshell behaviour of a chicken egg. Proc. Int. Conf. Noise and Vibration Engineering (ISMA23), September 16-18, Leuven, Belgium.

De Ketelaere, B., Govaerts T., Coucke P., Dewil E., Visscher J., Decuypere E., and De Baerdemaeker J., 2002. Measuring the eggshell strength of 6 different genetic strains of laying hens: Techniques and comparisons. British Poultry Sci., 43, 238-244.

Denys S., Pieters J.G., and Dewettinck K., 2006. Combined CFD and experimental approach for determination of the surface heat transfer coefficient during thermal processing of eggs. J. Food Sci., 68, 943-951.

Havlíček M., Nedomová Š., Simeonovová J., Severa L., and Křivánek I., 2008. On the evaluation of chicken egg shape variability. Acta Universitatis Agriculture et Silviculture Mendelianae Brunensis, 56, 69-74.

Ju B.F., Liu K.-K., Ling S.-F., and Hong Ng W., 2002. A novel technique for characterizing elastic properties of thin biological membrane. Mechanics of Materials, 34, 749-754.

Macleod N., Bain M., and Hancock J., 2006. The mechanics and mechanisms of failure of hens' eggs. Int. J. Fracture, 142, 29-41.

Narushin V.G., 2001. Shape geometry of the avian egg. J. Agric. Eng. Res., 79, 441-448.

Sarica M. and Erensayin C., 2004. Poultry Products. Bey-Ofset Press, Ankara, Turkey.