ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS
SBORNÍK MENDELOVY ZEMĚDĚLSKÉ A LESNICKÉ UNIVERZITY V BRNĚ

Ročník LV 14 Číslo 1, 2007

THE EFFECT OF THE EGG`S SHAPE ON THE STRESS DISTRIBUTION IN THE EGGSHELL AT INTERNAL PRESSURE LOADING

Š. Nedomová, J. Buchar, I. Křivánek

Received: January 8, 2007

Abstract

NEDOMOVÁ, Š., BUCHAR, J., KŘIVÁNEK, I.: *The effect of the egg`s shape on the stress distribution in the eggshell at internal pressure loading*. Acta univ. agric. et silvic. Mendel. Brun., 2007, LV, No. 1, pp. 129–142

The influence of the eggshell shape on the stress distribution under internal pressure is studied. A mathematical description of the hen`s eggshell is proposed. The analytical expressions for the membrane solution are presented. Obtained results are used for the evaluation of a set of domestic hen`s eggs. 28 eggs were analysed in this study. The weight of eggs ranged from 49.55 g to 61.08 g, the egg shape ranged from 72.82 % to 84.94 %, the average eggshell thickness ranged from 0.343 to 0.433 mm. The eggshell strength is given namely by the maximum values both of meridian and circumferential forces. The dependence of the meridian force maximum on the egg shape index has some tendency to increase with egg shape index. The outlined linear dependence is very weak, the coefficient of correlation is about 0.45.

eggshell, elasticity, internal pressure, membrane analysis

The egg quality is mostly described by the value of the eggshell strength (Lin J. et al., 1995; Carnarius et al., 1996; Rezac et al., 2000; Nirasawa et al., 1998; Picman and Pripil, 1997). Máchal and Simeonovová (2002) mention the strength of eggshell from 29.05 N to 36.46 N. Positive correlations existed between strength of eggshell and index shape, also between strength of eggshell and ratio of eggshell (Máchal and Simeonovová, 2002). This strength is affected by many factors (thickness, porosity, chemical composition etc.). One of them, which should be always included when discussing the strength of eggshell, is their shape. There are various experimental techniques of the eggshell strength measurement [see for review e.g. Bain (1997)]. The most widely used is e.g. the quasi-static compression test which corresponds to the loading of eggs during their packing. During this test, eggs are compressed between two parallel plates by a steadily increasing load until failure results. This procedure enables to determine the force and the shortening of the egg at the moment of failure. These parameters are affected by the factors mentioned above. The exact evaluation should lead to the values of stress and strain at the failure. This procedure is relatively very easy if we use the specimen of a simple form (mostly cylindrical shape). Because the eggs exhibit a more complicated geometry, this procedure must use some numerical procedure like finite element method. The finite element method has been used in some papers (Manceau and Henderson, 1970; Entwistle et al., 1995; Buchar et al., 2001, 2003). In order to obtain some insight on the influence of the eggshell shape on the strength some analytical solutions are desirable. This solution is possible to obtain for experiments when eggs are subjected to internal pressure (see Entwistle and Reddy, 1996). In the given paper we are focused on the study of the influence of the egg shape. Eggs of domestic hens (Laying crossbreed of lines Rhode Island Red, Rhode White and Sussex light) have been used. For the given eggs we performed a computation of the stress distribution during their loading by the internal pressure. The aim of this effort consisted in the evaluation of the influence of the variations in the egg shape on the values of principal stresses in the eggshell. These stresses determine the eggshell strength.

MATERIAL AND EXPERIMENTS

The eggs described in the previous chapter have been used for the study of the influence of the egg shape. The weight, width, height and eggshell thickness are given in Table I. The width and height of the egg are used for the definition of the egg shape index:

Egg shape index = width/height × 100 (%).

I: *Main characteristics of the tested eggs*

Egg number	**weight** (g)	**length** (cm)	**width** (cm)	**egg shape index** (%)	**eggshell thickness** (mm)			
					sharp end	**blunt end**	**middle of egg**	**average**
6562	58.24	5.48	4.34	79.20	0.410	0.420	0.415	0.415
6563	56.78	5.46	4.30	78.75	0.420	0.400	0.410	0.410
6564	57.41	5.53	4.30	77.76	0.420	0.380	0.420	0.407
6565	55.51	5.40	4.30	79.63	0.350	0.360	0.320	0.343
6566	54.81	5.53	4.21	76.13	0.420	0.430	0.420	0.423
6567	56.82	5.74	4.18	72.82	0.390	0.390	0.380	0.387
6568	55.97	5.45	4.28	78.53	0.410	0.420	0.420	0.417
6569	53.00	5.35	4.21	78.69	0.380	0.385	0.365	0.377
6570	59.13	5.59	4.31	77.10	0.390	0.430	0.395	0.405
6571	54.79	5.50	4.19	76.18	0.420	0.420	0.420	0.420
6572	58.19	5.62	4.31	76.69	0.410	0.410	0.390	0.403
6573	49.55	5.34	3.98	74.53	0.420	0.420	0.420	0.420
6574	59.51	5.61	4.35	77.54	0.390	0.360	0.420	0.390
6575	54.78	5.50	4.18	76.00	0.430	0.380	0.410	0.407
6576	61.08	5.66	4.36	77.03	0.400	0.370	0.390	0.387
6577	59.04	5.56	4.31	77.52	0.415	0.430	0.400	0.415
6578	53.67	5.35	4.21	78.69	0.380	0.400	0.380	0.387
6579	51.90	5.30	4.14	78.11	0.450	0.440	0.410	0.433
6580	53.81	5.35	4.23	79.07	0.365	0.350	0.350	0.355
6581	57.77	5.42	4.39	81.00	0.400	0.390	0.370	0.387
6582	59.19	5.58	4.31	77.24	0.410	0.410	0.390	0.403
6583	51.57	5.15	4.20	81.55	0.390	0.390	0.380	0.387
6584	55.45	5.48	4.26	77.74	0.380	0.355	0.360	0.365
6585	60.47	5.55	4.41	79.46	0.430	0.420	0.405	0.418
6586	50.44	4.98	4.23	84.94	0.410	0.390	0.375	0.392
6587	56.47	5.30	4.35	82.08	0.380	0.390	0.370	0.380
6588	59.69	5.54	4.35	78.52	0.410	0.410	0.395	0.405
6589	52.45	5.34	4.20	78.65	0.410	0.390	0.390	0.397
6590	51.79	5.17	4.18	80.85	0.415	0.400	0.375	0.397
6591	51.96	5.23	4.18	79.92	0.430	0.430	0.420	0.427
Average	**55.71**	**5.44**	**4.26**	**78.37**	**0.405**	**0.399**	**0.392**	**0.399**

The shape of the egg has been determined from the digital photo of the egg by the procedure described by Barton and Krivanek (2001). The egg shape can be described by the parametric equations:

$$x = a\cos(\varphi),\ y = a\sin(\varphi),$$

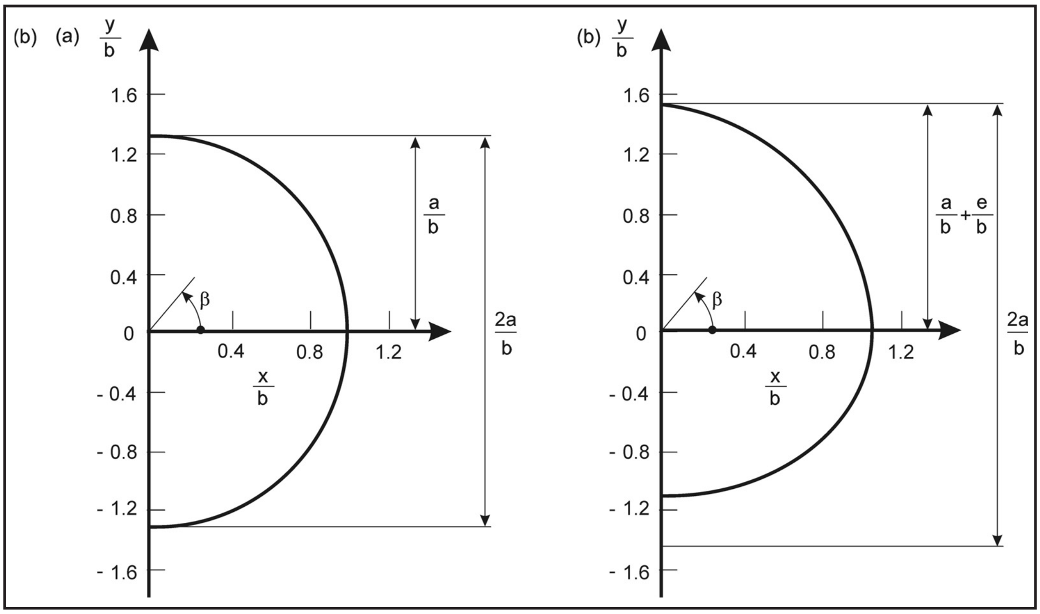
where

$$a = k_1 \frac{1 + k_2\cos(\varphi)}{\sqrt{k_3\cos^2(\varphi) + \sin^2(\varphi)}}.$$

This description has been used in Buchar et al. (2001, 2003). Another expression has been obtained by analysing the results obtained by Entwistle et al. (1996). This procedure is based on the shape of an eliptical profile. The parametric form of this profile is given by well known equations:

$x = b\cos\theta \qquad y = a\sin\theta,$

where a and b are the semi-major and semi-minor axes, respectively – see Fig. 1.



1: *Schematic of the meridian shape; a – ellipse, b – modified ellipse*

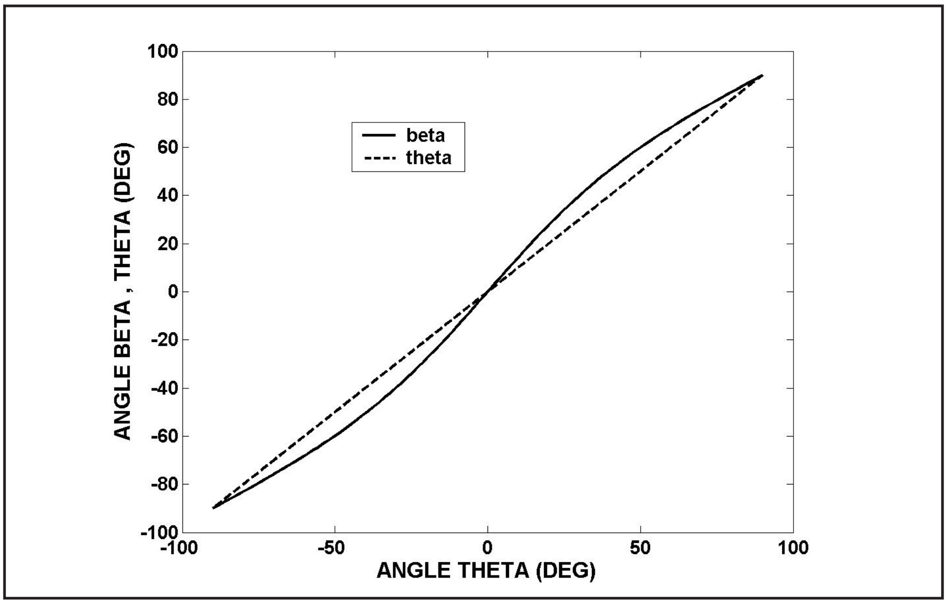
The meridian of the egg is described by a modification of these equations – see Kitching (1997).

$x = b\cos\theta \qquad y = (a + e\sin\theta)\sin\theta,$

where e/b is relatively small. The meaning of single parameters is shown in Fig. 1b. The angle β shown in Fig. 1 is given by

$$\mathrm{tg}\beta = \left(\frac{a}{b} + \frac{e}{b}\sin\theta\right)\mathrm{tg}\theta.$$

The example of the relation between the angles θ and β is shown in Fig. 2.



2: *The dependence of the angle β on the angle θ (a = 2.74 cm, b = 2.17 cm, e = 0.4 cm)*

The egg shape index is than given by the ratio b/a. This second approach seems to be more convenient because the single parameters are easily measurable. Their values are given in Table II.

II: *Parameters of the parametric equation describing the eggshell shape*

Egg number	**length** (cm)	**width** (cm)	**egg shape index** (%)	**a** (cm)	**b** (cm)	**e** (cm)
6562	5.48	4.34	79.20	2.740	2.170	0.400
6563	5.46	4.30	78.75	2.730	2.150	0.420
6564	5.53	4.30	77.76	2.765	2.150	0.410
6565	5.40	4.30	79.63	2.700	2.150	0.380
6566	5.53	4.21	76.13	2.765	2.105	0.350
6567	5.74	4.18	72.82	2.870	2.090	0.430
6568	5.45	4.28	78.53	2.725	2.140	0.470
6569	5.35	4.21	78.69	2.675	2.105	0.360
6570	5.59	4.31	77.10	2.795	2.155	0.310
6571	5.50	4.19	76.18	2.750	2.095	0.320
6572	5.62	4.31	76.69	2.810	2.155	0.350
6573	5.34	3.98	74.53	2.670	1.990	0.380
6574	5.61	4.35	77.54	2.805	2.175	0.420
6575	5.50	4.18	76.00	2.750	2.090	0.400
6576	5.66	4.36	77.03	2.830	2.180	0.450
6577	5.56	4.31	77.52	2.780	2.155	0.430
6578	5.35	4.21	78.69	2.675	2.105	0.460
6579	5.30	4.14	78.11	2.650	2.070	0.390
6580	5.35	4.23	79.07	2.675	2.115	0.370
6581	5.42	4.39	81.00	2.710	2.195	0.310
6582	5.58	4.31	77.24	2.790	2.155	0.320
6583	5.15	4.20	81.55	2.575	2.100	0.350
6584	5.48	4.26	77.74	2.740	2.130	0.360
6585	5.55	4.41	79.46	2.775	2.205	0.430
6586	4.98	4.23	84.94	2.490	2.115	0.390
6587	5.30	4.35	82.08	2.650	2.175	0.330
6588	5.54	4.35	78.52	2.770	2.175	0.380
6589	5.34	4.20	78.65	2.670	2.100	0.410
6590	5.17	4.18	80.85	2.585	2.090	0.450
6591	5.23	4.18	79.92	2.615	2.090	0.400
Average	**5.44**	**4.26**	**78.40**	**2.718**	**2.130**	**0.390**

The knowledge of the parametric equations x(θ), y(θ) enables to evaluate the expression for the coordinates of the center of the meridian curvature, x_0, y_0:

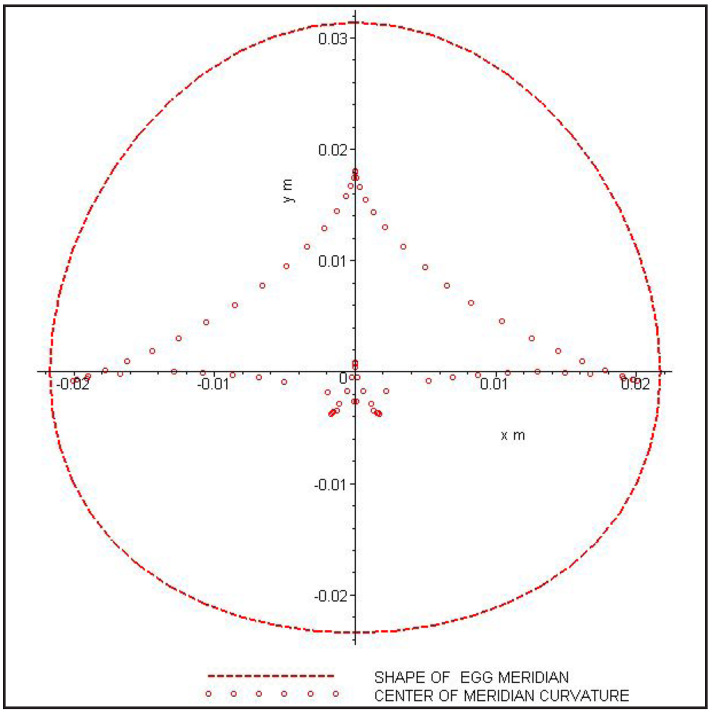
$$x_0 = \frac{[8e^3\sin^3\theta + ae\sin\theta(a + 2e\sin\theta) + a(a^2 - b^2)]}{(2e\sin^3\theta + a)b}\cos^2\theta$$

$$y_0 = \frac{(a^2 - b^2 - 4e^2)\sin\theta + 6e\sin\theta(e\sin\theta + a) - 3ae}{2e\sin^3\theta + a}.$$

The radius of the curvature R is given by the expression:

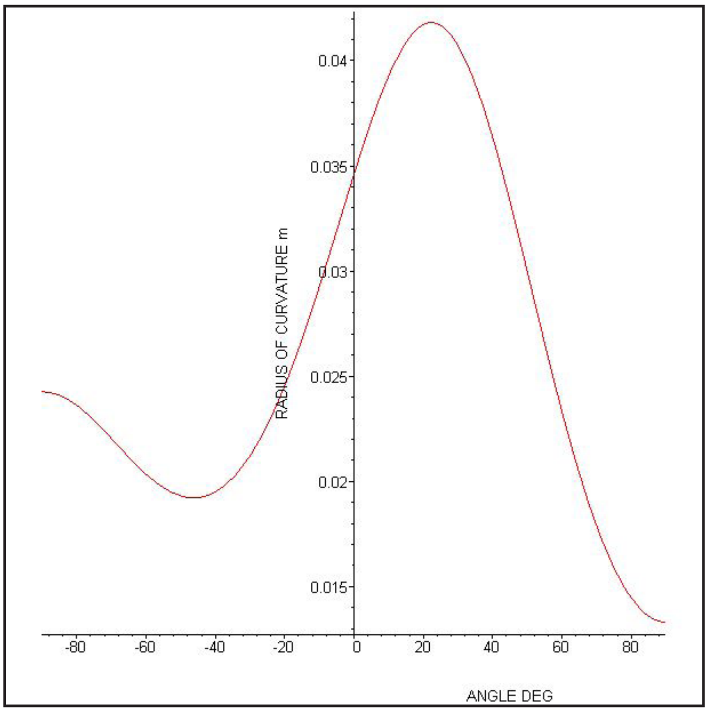
$$R = \sqrt{(x(\theta) - x_0)^2 + (y(\theta) - y_0)^2}.$$

In Fig. 3 the example of the meridian shape and positions of the curvature center is displayed.



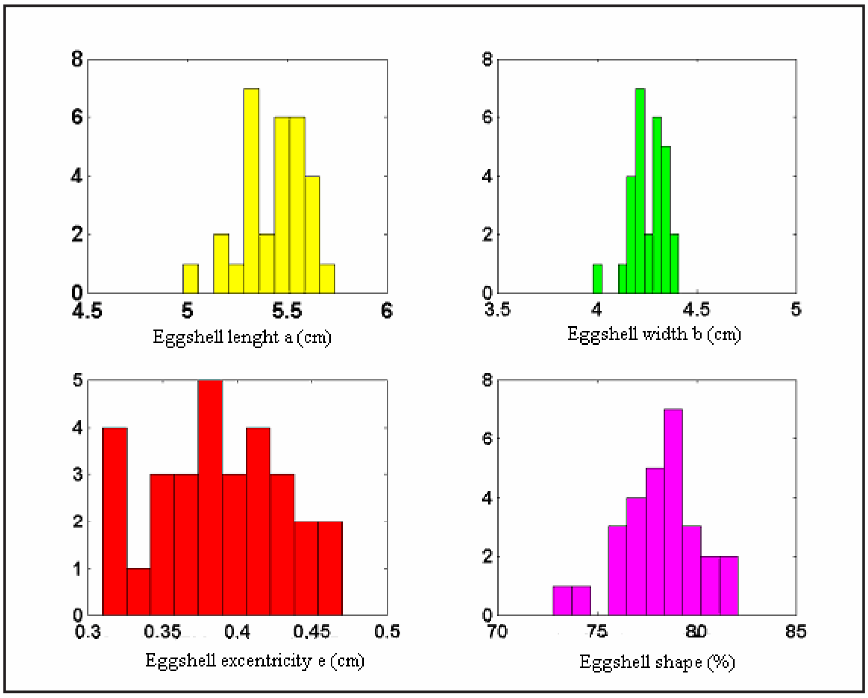
3: *Egg meridian shape and center of the meridian curvature. Egg No 6562 in Table II.*

The radius of the curvature is shown in Fig. 4.



4: *Radius of the curvature. Egg No 6562.*

The values of parameters a, b and e which determine the shape of egg exhibit a relatively large scatter. Eggshell thickness exhibits the same tendency. The distribution of these parameters is shown in Fig. 5.

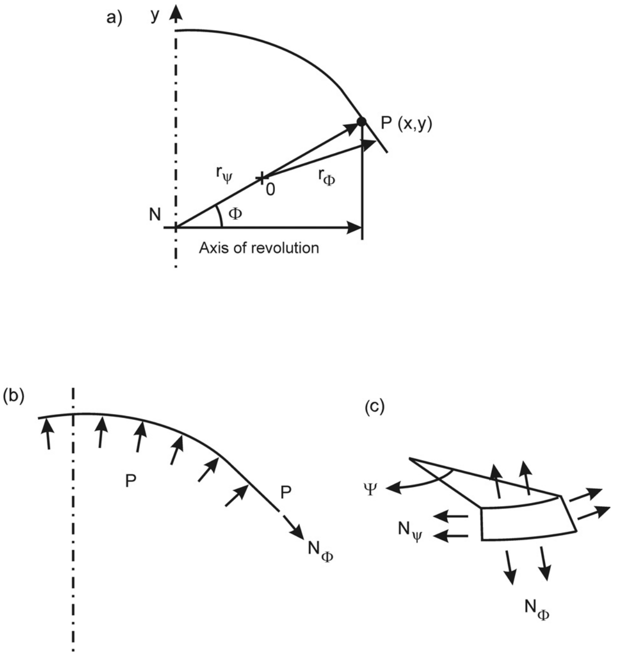


5: *Distrubution of the main parameters given in Table II*

The more detailed analysis of the given data leads to the conclusion that the parameters describing the eggs shape are independent of the eggshell thickness. The parametric equations of the egg meridian have been used for the evaluation of elastic stress and strain distribution in the pressurised eggshell using of the finite element method (Entwistle et al., 1996). Even if this method is very effective, it´s use is too complicated for the evaluation of the egg shape effect. For these purposes some analytical solution of the stress distribution is desirable. If we take into account that the thickness to principal radius ratio is always very small in any position and there are no rapid change of shape or discontinuity in the shell the membrane analysis can provide this analytical solution without any significant error.

STRESS ANALYSIS

The schematic of the membrane analysis (see e.g. Šejnoha and Bittnarová, 1999) is shown in Fig. 6.



6: *Description of the eggshell stress analysis; a – geometry, b – forces on cap above point P, c – in plane forces on element at point P*

According to this figure the forces on the element of the eggshell is given by

$$2\pi r_o N_\Phi \cos\Phi = \pi r_o 2p$$

$$\frac{N_\Phi}{r_\Phi} + \frac{N_\Psi}{r_\Psi} = p,$$

where r_Φ, r_Ψ are meridian and circumferential (principal) radius of curvature at P, and N_Φ, N_Ψ are the principal forces per unit length of shell in the meridian and circumferential directions at P. P is the internal pressure and shell thickness is denoted as t.

Solution of the above equations is

$$N_\Phi = \frac{pr_o}{2\cos\Phi} = \frac{pr_\Psi}{2}$$

$$N_\Psi = \frac{pr_{\chi\Psi}}{2}\left(2 - \frac{r_\Psi}{r_\Phi}\right).$$

The gradient of normal at P is given by:

$$\mathrm{tg}\Phi = -\frac{\dfrac{dx}{d\theta}}{\dfrac{dy}{d\theta}}.$$

If we use the parametric equations we obtain:

$$\mathrm{tg}\Phi = \frac{b\sin\theta}{\cos\theta(a + 2e\sin\theta)}.$$

This expression is useful for the evaluation of the next geometric characteristics:

$$r_\Phi = \frac{1 + \left(\dfrac{dy^2}{dx}\right)^{3/2}}{\dfrac{d^2y}{dx^2}}$$

$$\frac{dy}{dx} = -\frac{\cos\theta[a + 2e\sin\theta]}{b\sin\theta}$$

$$\frac{d^2y}{dx^2} = \frac{\dfrac{d}{d\theta}\left(\dfrac{dy}{dx}\right)}{\dfrac{dx}{d\theta}} = -\frac{a + 2e\sin^3\theta}{b^2\sin^3\theta}.$$

The use of these expressions leads to:

$$r_\Phi = \frac{[\cos^2\theta(a + 2e\sin^3\theta) + b^2\sin^2\theta]^{3/2}}{b(a + 2e\sin^3\theta)}.$$

Very similar procedure gives the expression:

$$r_\Psi = \frac{b[(a + 2e\sin\theta)^2 + b^2\sin^2\theta]^{1/2}}{a + 2e\sin\theta}.$$

Now we obtain expressions for the forces:

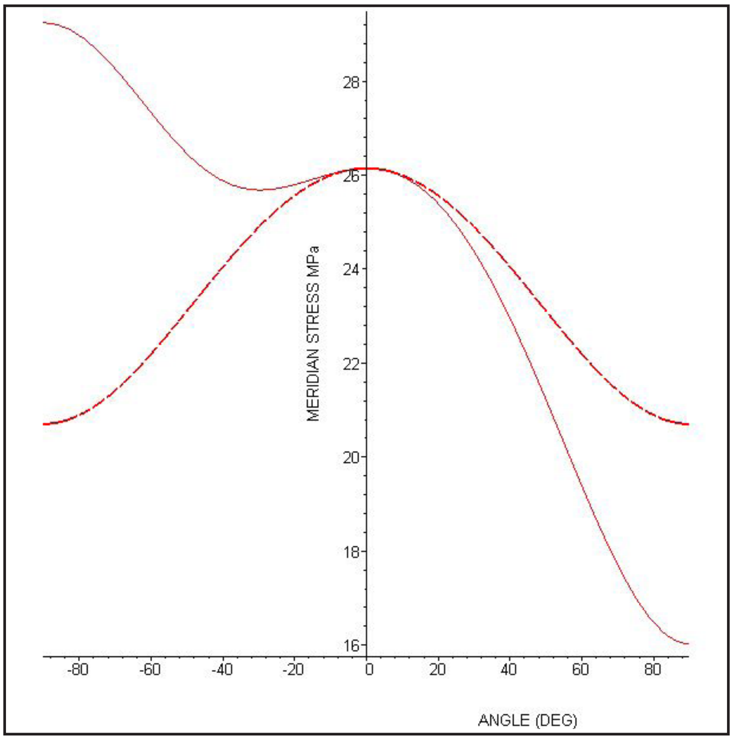
$$N_\Phi = \frac{1}{2}pb\,\frac{\sqrt{(a + 2e\sin\theta)^2\cos^2\theta + b^2\sin^2\theta}}{a + 2e\sin\theta}$$

$$N_\Psi = \frac{1}{2}pb\,\frac{\sqrt{(a + 2e\sin\theta)^2\cos^2\theta + b^2\sin^2\theta}}{a + 2e\sin\theta}\left\{2 + b^2(a + 2e\sin^3\theta)\,\frac{\sqrt{(a + 2e\sin\theta)^2\cos^2\theta + b^2\sin^2\theta}}{(a + 2e\sin\theta)\,[b^2\sin^2\theta + (a + 2e\sin\theta)^2]}\right\}^{3/2}.$$

Stresses (σ_Φ,σ_Ψ) are calculated by dividing corresponding forces by the thickness t.

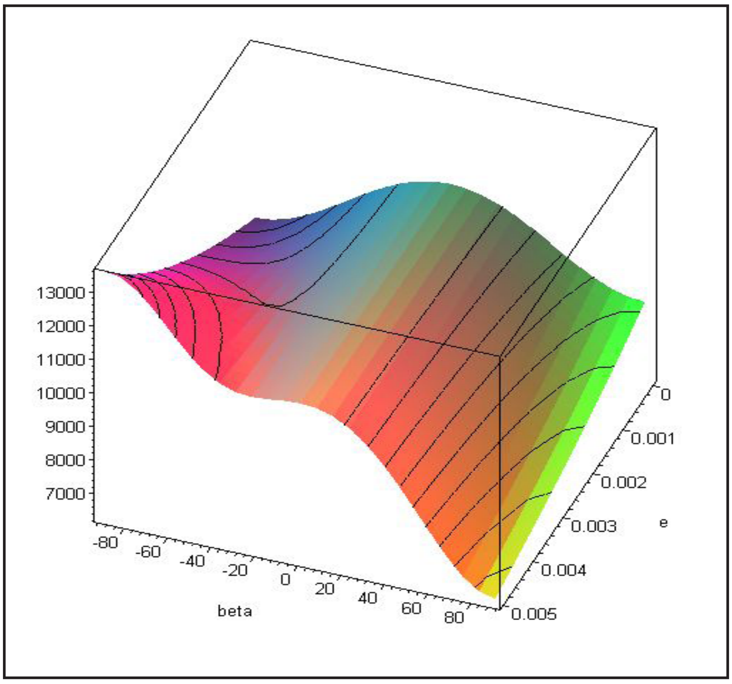
RESULTS

In the given chapter the obtained equations will be analyzed for the dimensions given in Table I and II and for the internal pressure of 1 MPa. In Fig. 7 the meridian stress is plotted against the angle β.



7: *Meridian stress for elliptical meridian and for the egg meridian. The dimensions for egg No 6562 are used.*

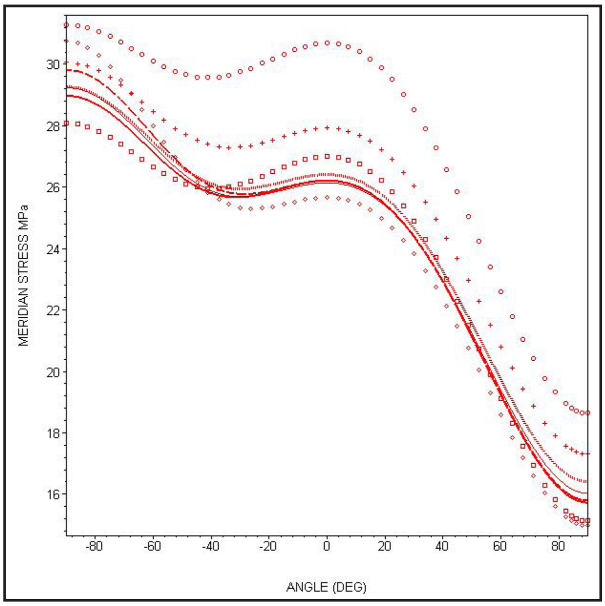
It is obvious that the excentricity e leads to some transition from symmetric distribution of stress to non-symmetric one. In order to give some insight on this effect the meridian force has been used. This force is not affected by the eggshell thickness. In Fig. 8 the influence of the parameter e on the meridian force distribution is shown.



8: *The distribution of the meridian force in the eggshell (Vertical axis in N/m). The values of a, b for the egg No 6562 have been used.*

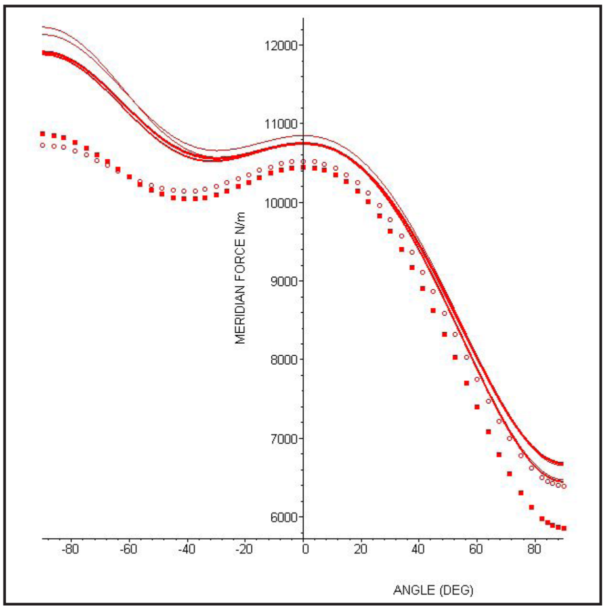
The increase in e generally leads to the shift of the maximum value of the stress towards to the blunt end of the egg. The same tendency may be reported for the circumferential stress and/or force, respectively.

In Fig. 9 the distribution of the meridian stress for the first 8 eggs from table II is shown. It may be seen that there is a relatively significant influence of the variation of parameters a, b, e and thickness.

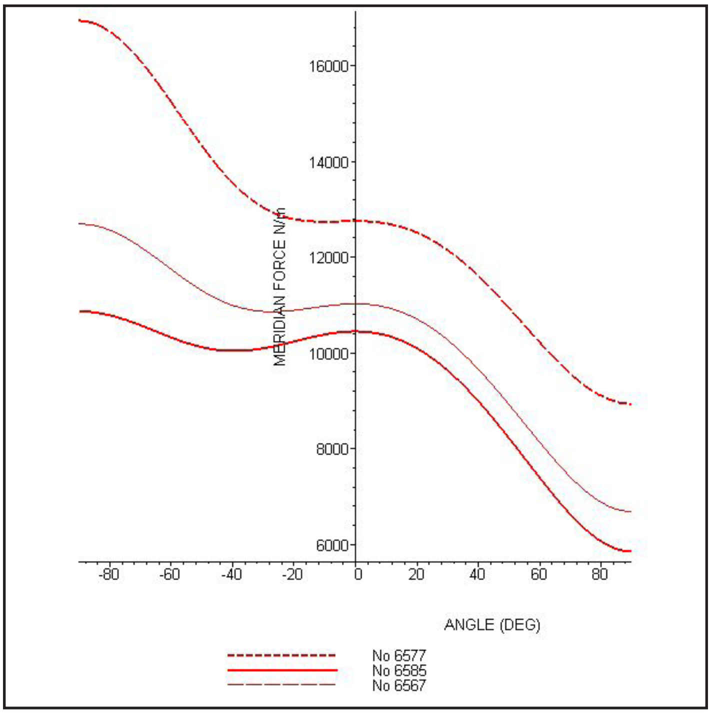


9: *Meridian stress distribution along to the angle β*

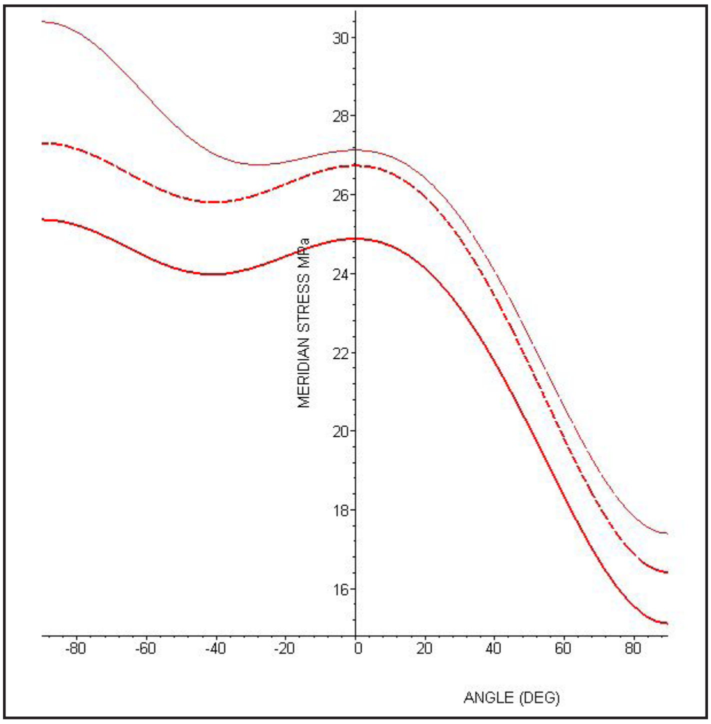
If we take the meridian force the influence of the thickness is excluded. The distribution of this force is given in Fig. 10. From this figure one can see that the measure of the variation in meridian forces increases from sharp to blunt end of egg. Looking on data in Table II one can see that there are groups of data with the same values of the parameter e. In Fig. 11 the distribution of the meridian forces for the eggs with e = 0.35 cm is plotted. The significant influence of the values of parameters a and b can be derived from this figure. These parameters describe the height and length of the specimen and thus the egg shape index. If we take into account the meridian stress, i.e. if we take the eggshell thickness the distribution is futher changed – see Fig. 12.



10: *Meridian force distribution along to the angle β. Notation of the lines and points is the same as in Fig. 9.*



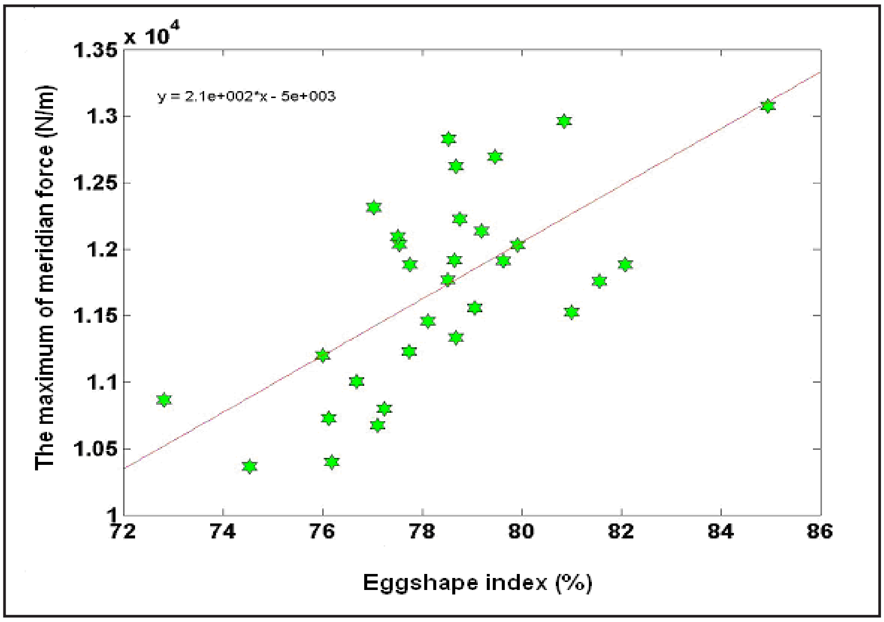
11: *Meridian force distribution along to the angle β. Excentricity e = 0.35 cm.*



12: *Meridian stress distribution along to the angle β. Excentricity e = 0.35 cm.*

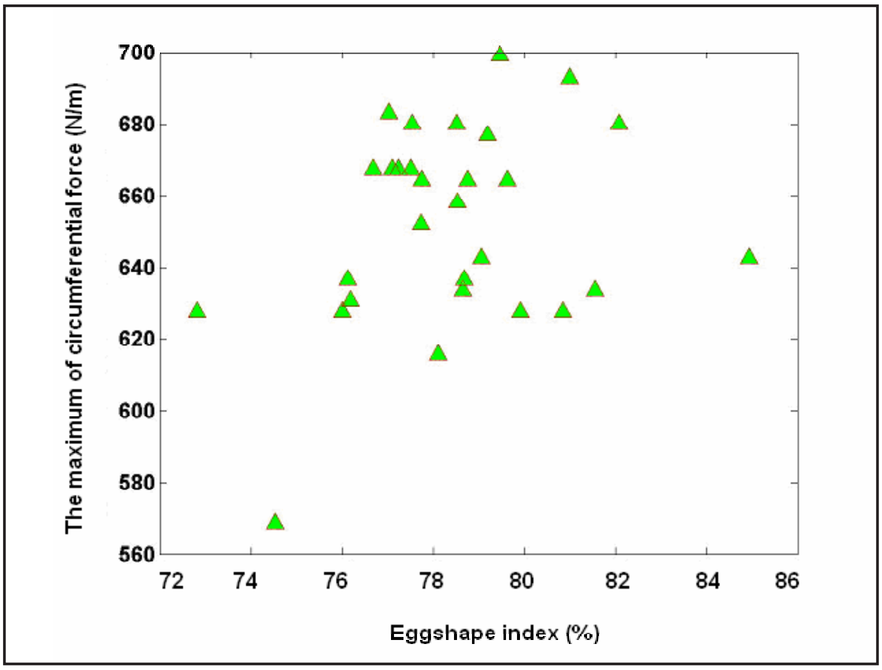
Similar conclusions have been obtained for some other groups of eggs with constant value of the parameter e. It means that a hypothesis may be postulated that the influence of the eggshell geometry can be described using the egg shape parameter b/a.

The eggshell strength is given namely by the maximum values both of meridian and circumferential forces. The dependence of the meridian force maximum on the egg shape index is given in Fig. 13. It may be seen that there is some tendency to increase of this force with egg shape index. The outlined linear dependence is very weak, the coefficient of correlation is about 0.45.



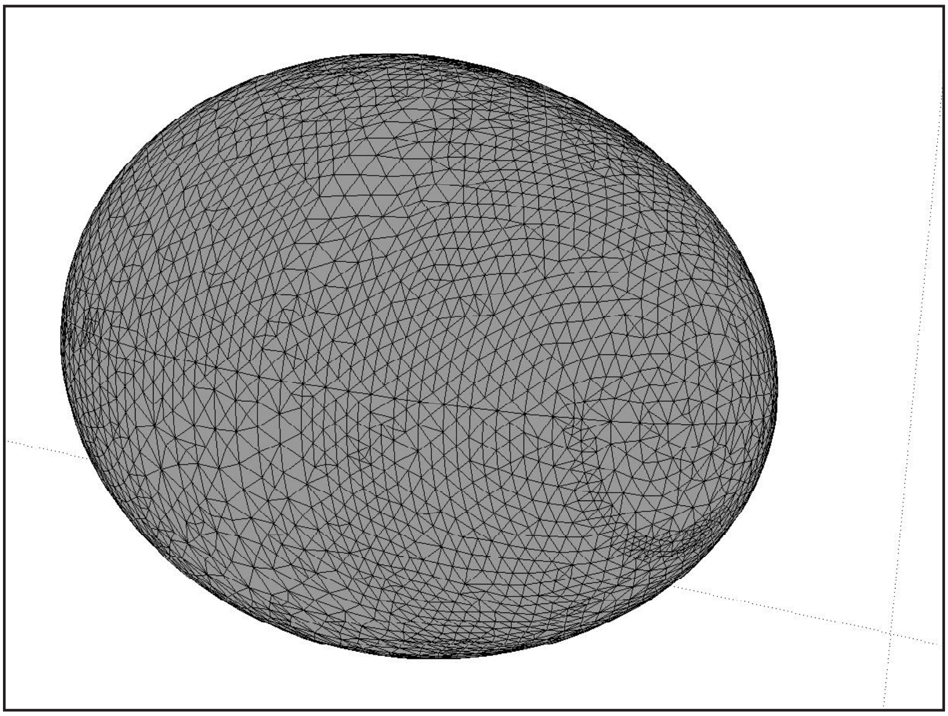
13: *The influence of the egg shape index on the maximum of the meridian force*

The maximum of the circumferential force maximum on the egg shape index is independent – see Fig. 14.



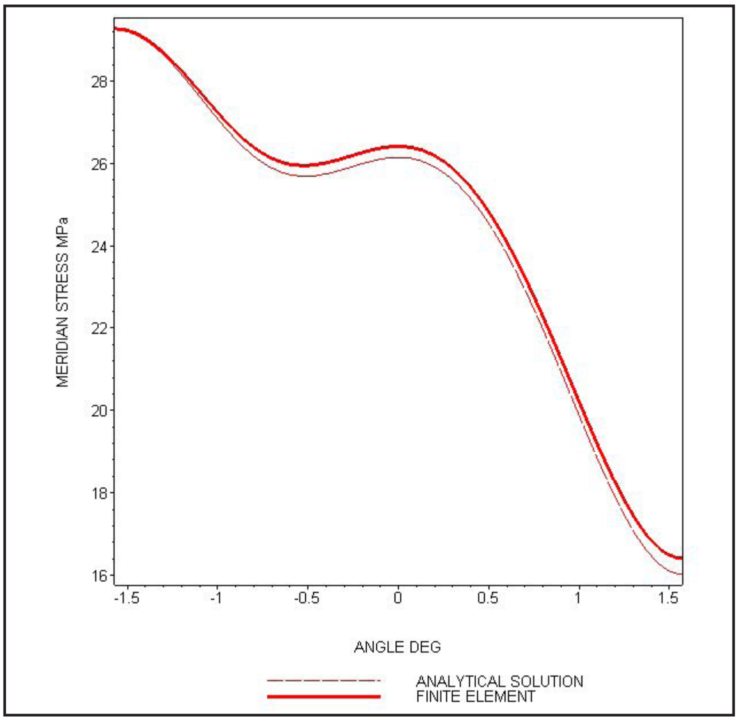
14: *The influence of the egg shape index on the maximum of the circumferential force*

The used theory of the stress evaluation in the eggshell is based on some assumptions which neglect e.g. bending and torsion effects etc. – see e.g. Šejnoha and Bittnarová (1999) for details. In order to decide if this simplification is admissible or not the finite element analysis, which effectively solved the full shell equations, has been performed. For the numerical simulation the FEMLAB software has been used see e.g. www.femlab.com for details. This software contains the structural mechanics modul which was applied for the solution of our problem. The eggshell has been substituted by finite elements of the shell type. An example of such finite element model of the eggshell is shown in Fig. 15. The element used for the shell application mode is of Mindlin–Reisneer type – see Allman (1988).



15: *The finite element model of the egg No 6562*

By using this method, we can find the distribution of the stress not only on the egg`s surface but also through the eggshell thickness. For our purposes the distribution of the meridian stress on the egg`s surface has been evaluated. An example of such distribution is displayed in Fig. 16. It may be seen that the stresses obtained by the analytical method are nearly identical with stresses obtained from numerical computation. Namely the maximum values of this stress are nearly identical. Similar results were obtained for all tested eggs. It is obvious that the used membrane analysis leads to very good results. For the given eggshell geometry, it is thus not necessary to use a numerical analysis which is generaly very complicated in comparison with the analytical solution.



16: *Distribution of the meridian stress in the eggshell (Egg No 5562)*

CONCLUSIONS

In the given paper the shape of eggs have been described by parametric equations which have been obtained by the modification of parametric equations for ellipsoid. These parametric equations involve three parameters a, b, e. The equations closely fitted the actual shape of eggs. The eggs from one line of hens collected on the same day differ in values of the above mentioned parameters very significantly. Pronounced difference in eggshell thickness can be also reported at the same time. The use of membrane analysis gives some insight on the stress distribution. Both stresses (meridian and circumferential) strongly depend on the position along the meridian. The maximum of both stresses has been found at the blunt end of the egg. Generally, the distribution of stress is dependent on all parameters, i.e. a, b, e and on the eggshell thickness. There is only a weak linear dependence of the maximum value of the meridian stress on the egg shape index. From the practical point of view the stress distribution in the eggshell must be evaluated for every egg. A reliable prediction of this distribution is probably impossible.

Nevertheless, it has also to be noted that the internal pressure is not likely to be the typically occurring load which eggshell has to withstand. A more typical loading represents e.g. the compression test described in the introduction. At this loading there is no chance to find some analytical solution. The stress distribution must be evaluated by the solution of the full shell equations. The results of this research should appear in some forthcoming papers.

SOUHRN

Vliv tvaru vajec na rozložení napětí ve vaječné skořápce při zatěžování vnitřním přetlakem

V práci je sledován vliv tvaru vajec na napětí ve skořápce při zatěžování vnitřním přetlakem. Toto, poněkud atypické, namáhání vaječné skořápky bylo zvoleno z důvodu možnosti stanovit napjatost pomocí analytických vztahů. Je navržen popis tvaru vajec ve formě modifikované elipsy. Při tomto popisu je tvar skořápky určen třemi parametry. Velikost těchto parametrů u vajec jedné linie slepic vykazuje značnou variabilitu. Ukazuje se, že velikost těchto parametrů nemá vztah k tloušťce skořápky. Pro hodnocení stavu napjatosti je použito mebránové teorie skořepin, kdy jsou zanedbávány ohybové a krouticí účinky. Porovnání s výpočtem pomocí metody konečných prvků, kdy tato zjednodušení nejsou použita, ukazuje, že zmíněná teorie dává výsledky prakticky shodné s výsledky uvedené numerické simulace. Jsou odvozeny vztahy pro membránové síly a napětí napětí ve vaječné skořápce. Ukazuje se, že veličiny se výrazně mění podél meridiánu (obrys řezu skořápky a roviny jdoucí osou rotace skořápky) a dosahují maximálních hodnot na tupém konci vaječné skořápky. Distribuce napětí a jejich velikosti závisí na parametrech určujících tvar vajec a na tloušťce vaječné skořápky. Z výsledků vyplývá, že neexistuje možnost predikce vlivu parametrů na velikost maximálních hodnot napětí. Jistou výjimku představuje maximum meridiánového napětí, které vykazuje lineární závislost na indexu, který popisuje tvar vajec. Tato závislost je však poněkud nižší. Napjatost tak musí být stanovována pro každé zkoumané vejce. To pak platí i pro případy zatěžování, kdy je třeba použít numerické simulace (stlačování vajec mezi dvěma deskami ap.).

vaječná skořápka, pružnost, membránová teorie skořepin, vnitřní přetlak, tvar vajec, napjatost

ACKNOWLEDGEMENT

The support of this work by the Internal Grant Agency of the Mendel University of Agriculture and Forestry under contract No: 4IG11/2004 is gratefully acknowledged.

REFERENCES

ALLMAN, J. D.: Evaluation of the constant strain triangle with drilling rotation. *Int. J. Numer. Engng*, 1988, 26, 12: 2645–2655.

BAIN, M.: A reinterpretation of eggshell strength. In: *Eggs and Eggshell quality (S. E. Solomon, Ed.)*, Manson Publishing/The Veterinary Press/Iowa State University Press, 1997, p. 131–142. ISBN 0813828279

BARTOŇ, S., KŘIVÁNEK, I.: Determination of parameters of egg`s perimeterby analysis of digital photography in Maple. *Proc. Of the Symposium on the Quality food evaluation*, March 8, Brno, 2001

BUCHAR, J., SIMEONOVOVA, J.: On the identification of the eggshell elastic properties under quasistatic compression. In: *19^{th} CAD – FEM USERS MEETING 2001 - International Congress on FEM Technology.*17–19. October 2001, Potsdam, Berlin Germany, Published by CAD – Fem GmbH, Munchen, 2001, Vol. 2, p 1–8

BUCHAR, J., NEDOMOVÁ, Š., SIMEONOVOVÁ, J.: Identification of the eggshell elastic properties. *Proc. of the 37th International Conference Experimental Stress Analysis,* Milovy, June 3–6, 2003. Brno: VUT, Fakulta strojní, 2003, p 5–6. ISBN 80-214-2314-5

CARNARIUS, K. M., CONRAD, K. M., MAST, M. G., MACNEILL, J. H.: Relationship of eggshell ultrastructure and Shell Strength to the Soundness of Shell Eggs. *Poultry Science* 1996, 75, 5: 656–663. ISSN 0032-5791

ENTWISTLE, K. M., SILYN-ROBERTS, H., OCHIENG ABUODHA, S.: The relative fracture strengths of the inner and outer surfaces of the eggshell of the domestic fowl. *Proceedings - Royal Society of London, Series B – Biological Sciences,* 1995, 262, 1364: 169–174. ISSN 0962-8452

ENTWISTLE, K. M., REDDY, T. Y.: The Fracture Strength under Internal Pressure of the Eggshell of the Domestic Fowl. *Proceedings – Royal Society of London, Series B – Biological Sciences,* 1996, 263, 1369: 433–438**.** ISSN 0962-8452

KITCHING, R.: Pressurised Eggshell Analysis.: *Int. J. Mech. Sci.*, 1997, 39, 4: 391–396. ISSN 0020-7403

LIN, J., PURI, V. M., ANANTHESWARAN, R. C.: Measurement of eggshell thermal – mechanical properties. *Transaction of the ASAE*, 1995, 38, 6: 1769–1776. ISSN 0001-2351

MÁCHAL, L., SIMEONOVOVÁ, J.: The relationship of shortening and strength of eggshell to some egg quality indicators and egg production in hens of different initial laying lines. *Arch. Tierz*., 2002, 45, 3: 287–296. ISSN 0003-9438

MANCEAU, J. R., HENDERSON, J. M.: Physical properties of eggshells. *Transactions of the American Society Agriculture Engineering,* 1970, 13: 436

NIRASAWA, K., TAKAHASHI, H., TAKEDA, H., FURUKAWA, T., TAKEDA, T., NAGAMINE, Y.: Restricted maximum likehood estimates of genetic parameters and genetics trends of chickens divergently selected for eggshell strength. *Journal of Animal Breeding and Genetics*, 1998, 115, 5: 375–382.

PICMAN, J., PRIPIL, S.: Is greater eggshell density an alternative mechanism by which parasitic cuckoos increase the strength of their eggs?, *Journal for Ornithology*, 1997, 138, 4: 531–541. ISSN 0021-8375

REZAC, P., POSCHL, M., HAVLICEK, Z.: Relationship of plasma oestradiol–17 beta and cholesterol levels to eggshell strength in laying hens. *Czech Journal of Animal Science,* 2000, 45, 7: 313–318.

ŠEJNOHA, J., BITTNAROVÁ, J.: *Shells (Skořepiny*). Lecture notes. Czech Technical University. Prague. 1999, 82 p. (in Czech) ISBN 80-01-01944-6

Address

Ing. Šárka Nedomová, Ústav technologie potravin, Mendelova zemědělská a lesnická univerzita v Brně, Zemědělská 1, 613 00 Brno, Česká republika, e-mail: snedomov@mendelu.cz, Prof. Ing. Jaroslav Buchar, DrSc., RNDr. Ivo Křivánek, CSc., Ústav techniky a automobilové dopravy, Mendelova zemědělská a lesnická univerzita v Brně, Zemědělská 1, 613 00 Brno, Česká republika, e-mail: buchar@mendelu.cz