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Shell, a Naturally Engineered Egg Packaging, As Estimated for Strength by Non-destructive Testing for Elastic Deformation

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Abstract

Eggshell is a naturally engineered packaging of its interior content and prediction of the egg fracture force (*F*) under non-destructive elastic shell deformation (*D*) remains a challenge. Specifically, since shell deflection function under a constant load is linear, it is difficult to calculate the maximum point for *F* and the respective value of *D*. The aim was to solve this problem experimentally by employing a measurement instrument commonly used to analyse the deformation of metals and alloys. The experiments were conducted on chicken eggs aligned in their morphological parameters. A curvilinear characteristic of the change in the function $F = f(D)$, was achieved at extremely low shell compression speeds (0.010 to 0.065 mm s^{-1}). This enabled us to (i) describe the obtained functions accurately with Gaussian curves; (ii) expand the range of non-destructive load on a chicken egg to 30 N; and (iii) develop empirical equations for a reasonably accurate prediction of maximum shell deformation ($R^2 = 0.906$) and shell strength ($R^2 \approx 1$). It is suggested that it is possible to calculate shell strength by measuring its deformation at five points that corresponded to non-destructive loads of 10, 15, 20, 25 and 30 N. The methodological approach proposed can be used for the development of an effective shell strength calculation procedure by non-destructive testing. It depends on the appropriate tool for assessing and controlling the elastic shell deformation as well as the features of strength properties of the studied eggs.

Keywords: Chicken eggs, egg fracture force, shell strength, elastic shell deformation, non-destructive testing

Nomenclature

a, b, c	Coefficients used for approximating the dependence $F = f(D)$
B	Egg maximum breadth
D	Shell deformation
$D_{\max}$	Maximum value of shell deformation
D_1 to D_5	Shell deformation at different compressions
F	Shell fracture force
$F_{\max}$	Maximum value of shell fracture force
F_1 to F_5	Different values of shell compressions
k_0 to k_{25}	Coefficients used for approximating the dependence $F = f(D_1 \ldots D_5)$
L	Egg length
v	Shell compression speed
W	Egg weight

1. Introduction

1.1. Eggshell strength evaluation

Besides their valuable nutritional properties, the uniqueness of bird eggs also lies in the formation of the shell, which can be considered as a naturally engineered packaging that reliably protects the egg contents from damage and can be considered nature's technical ceramic (Hahn et al., 2017). Shell strength is one of the key characteristics to safeguard the egg integrity and egg quality in general, and is, therefore, critical for poultry industry, egg incubation, storage, and breeding (Romanov, 1995; Narushin, 1998; Narushin and Romanov, 2000; Shomina et al., 2009a). Availability of effective non-destructive techniques for evaluating the shell strength and other egg quality properties (Voisey et al., 1979; Narushin et al., 2021) is essential, among various potential applications, for improving hatchability (Narushin and Romanov, 2001, 2002a,b,c; Narushin et al., 2002; Shomina et al., 2009b; Tagirov et al., 2009b) and developing methods to detect chick sex *in ovo* (Narushin et al., 1994, 1996, 1998; Romanov et al., 1994) and model embryo growth (Narushin et al., 1994, 1997).

A complete mechanisation of the industrial production of table eggs, along with their undoubtedly positive commercial benefits, has entailed a number of risks arising in the logistic chain of transporting eggs from a hen house to end consumers. The problem of safe egg storage and preservation is also important for egg incubation and the hatching egg industry (e.g., Tagirov et al., 2009a; Shomina et al., 2009a). All these aspects may be addressed by engineering approaches, such as the development of the appropriate mechanisms of a small impact on this natural object, and through the implementation of targeted breeding and genetic progress in creating and improving layer crosses aimed at increasing the shell strength. To employ the engineering modus operandi, analysis of the egg strength characteristics can be completed by destructive methods, however this is wasteful because of the broken eggs. To explore relationship of the morphological, physical, geometric and other egg characteristics with the strength of its shell, studies of egg properties should therefore be carried out using non-destructive techniques.

When Schoorl and Boersma (1962) presented an apparatus for the non-destructive assessment of shell strength at the 1962 World Poultry Congress in Sydney, problems with analytical egg research seemed to be a thing of the past. The operation principle of their device consisted in exposing the egg to a constant load of 500 g, which did not cause its destruction, and measuring the degree of shell deflection, its value being an indicator of shell strength. As a result of this research, the authors identified relationship between the shell strength and value of its non-destructive deformation that correlated at the level of $R = 0.59$ to 0.88. Despite such a high correlation coefficient, the prediction accuracy was satisfied only by about 40 to 75% of a measured egg sampling. To improve accuracy, the authors suggested increasing the load size be increased to 1000 g or more.

A further significant contribution to the study of this method was made by Voisey and co-workers, who, over a decade of research, improved analytical tools (Voisey, 1975; Voisey and Hamilton, 1976; Voisey and MacDonald, 1978), whilst also increasing the non-destructive test load to 1.1 kg. They suggested that the higher degree of loading (up to 1.75 kg), the greater deformation and the better estimate. Dependence on the magnitude of the load on shell deformation has also been investigated, demonstrating a linear relationship (Voisey and Hunt, 1967, 1969; Voisey and Robertson, 1969) and optimising the shell compression test speed (Voisey and Hunt, 1969, 1976). However, through their studies, this team of authors was able to show that non-destructive deformation can be used to predict the magnitude of the destructive compressing load only in 54% of the sample of chicken eggs (Voisey and Hamilton, 1976; Voisey and Hunt, 1976; Voisey et al., 1979). Interestingly, the hypothesis of including a number of geometric characteristics of the egg in the prediction algorithm was accepted, but the resulting improvements it brought were too small (Voisey and Hunt, 1976).

In our earlier study (Narushin and Morgun, 1995), there was even a lower correlation (0.47) between shell fracture force and non-destructive elastic deformation, which showed that it was possible in only a little more than 20% of the eggs examined to make a more or less adequate estimate. Similarly, Voisey and Hunt (1976) were unable to demonstrate any special effect by including a number of other egg parameters in the prediction assay (Narushin and Chausovsky, 1997). Thus, further development of non-destructive prediction technology of the shell strength using deformation remains of current research interest in poultry science and engineering and we could expect significant improvements if non-destructive results could be married with the results of destructive experiments.

1.2. Optimisation of shell compression speed

While performing eggshell strength analysis, Carter (1977) considered the shell compression speed as one of three fundamental factors affecting the fracture force magnitude, in addition to (i) a group of such shell characteristics as its thickness, curvature, thickness of its weak inner layer, and degree of glossiness and roughness; and (ii) a group of mechanical design characteristics of the compressing body device at the point where it exerts pressure on the egg.

Voisey and Hunt (1969), investigating compression speeds from 0.008 to 16.7 mm s^{-1}, recommended applying pressure on the egg at 3.3 mm s^{-1} to ensure the minimum prediction error. Carter (1977), analysing the results of previous studies on this subject, particularly those conducted by Voisey and co-workers, suggested that a very wide range of speeds, i.e., from 20 µm s^{-1} to 1.1 m s^{-1}, could be used for industrial purposes. Thus, with a logarithmic increase in speed, a linear increase in the destructive compressing load would occur. A similar dependence was observed in the studies of Nedomová et al. (2014, 2016) and Trnka et al. (2016) at compression speeds from 0.0167 to 13.36 mm s^{-1}. However, Altuntaş and Şekeroğlu (2008) noticed that lower compression speeds required more force to break hen eggshells. In that study, they investigated a range of speeds between 0.33 and 0.99 mm s^{-1} leading to the conclusion that lower egg compression speeds have a slightly different effects on this dependence as reported by Carter (1977).

1.3. Function of changing the elastic shell deformation

Most of the studies conducted on the character of dependence of shell deformation under load have revealed its linear nature (Voisey and Hunt, 1967; Voisey and Robertson, 1969; Carter, 1970; Narushin et al., 2003; Macleod et al., 2006; Altuntaş and Şekeroğlu 2008; Nedomová et al., 2014; 2016; Juang et al., 2017). That is, under the impact of load, the shell deflection is described linearly, and destruction occurs at a certain stage, as a result of which the linear graph is interrupted. Graphical images of these dependencies have been provided by many authors (e.g., Macleod et al., 2006; Altuntaş and Şekeroğlu, 2008; Nedomová et al., 2014).

However, the graph of a linear function is extremely inconvenient for prediction purposes because it does not allow determination of an extremum using mathematical methods. In this regard, a curvilinear relationship would be more appropriate. To the best of our knowledge, results of only few studies suggest a curvilinear dependence. Nedomová et al. (2009) reported that egg compression can be described as a function of shell deformation by a 4th order curve. Hahn et al. (2017) demonstrated a curvature of the linear relationship, especially when studying avian species that lay eggs with stronger shells. This is most likely due to the fact that in these studies the authors used pads made of plastic materials at the point of contact with the egg. Thus, design of an instrument used to test the shell strength and record the magnitude of shell deflection is imperative.

Carter (1978) also introduced a concept of ‘delayed shell fracture’, which given an appropriate static load on the shell at a lower compression speed is a normal phenomenon that can be observed without difficulty. Therefore, it is possible to achieve a plateau at the peak of compression prior to the shell breakage, which will allow the linear function to be replaced by a curve. Knowing the formula of this curve, one could predict the maximum fracture force that the shell of a given egg can withstand.

In summary, we suggest that it could be feasible to improve the reliability of predicting shell strength from the magnitude of its non-destructive deformation if (i) the degree of non-destructive egg compression was maximised, without reaching the threshold value for damage;

and (ii) change the character of shell compression from rectilinear to curvilinear, which could provide more opportunities for analytical prediction of breakage. Based on these hypotheses, the goal of the present research was to develop methods to control the shell compression mechanics as well as an analytical method for processing the results obtained.

2. Materials and Methods

For the present study, 45 table eggs were selected from 23- to 35-week-old Hy-Line W36 laying hens from Yasensvit LLC, Kyiv Region, Ukraine. Each egg was weighed, and their length and maximum breadth measured.

As mentioned earlier, the design of a tool for measuring the magnitude of shell deformation can be of no small importance both for ensuring the required compression speed mode, and for obtaining a curvilinear relationship between deformation and the applied compression. For this purpose, an experimental instrument ZD-100Pu developed at the Department of Strength of Materials, National University of Life and Environmental Sciences, Ukraine was utilised. It was previously used in the studies on other experimental objects such as aluminium alloys (Chausov et al., 2020), chicken bone material (Chausov et al., 2018), and heat-resistant steel specimens (Marushchak et al., 2010). This device meets all the necessary requirements both in terms of proper measuring the compression speed and the functional dependence of compression on deflection magnitude.

A detailed description of this measurement tool is available elsewhere (Chausov et al., 2004). A scheme showing the main elements of the experimental setup is presented in Fig. 1. In short, the instrument includes (i) an immobile and moving crossheads between which the test sample is located; (ii) a device for providing variable rigidity of the compression system due to which compression is applied in a nonlinear mode; and (iii) a computer-controlled measuring system for conducting tests and processing test results. The key feature of this instrument is that it works on the principle of using the method of full deformation diagrams. That is, the deformation of a sample does not stop at the moment of its destruction and/or damage.

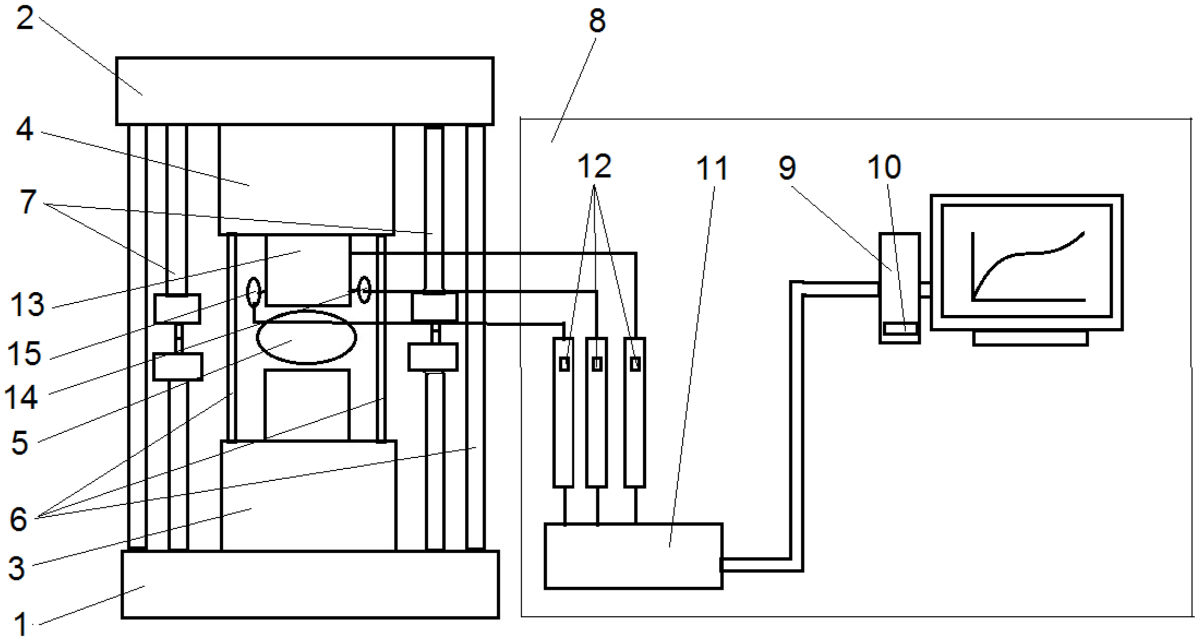


Fig. 1. Scheme of the experimental instrument ZD-100Pu (adopted from Chausov et al., 2004). 1, fixed crosshead; 2, moving crosshead; 3, grip connected to the fixed crosshead; 4, grip connected to the moving crosshead; 5, test specimen; 6, device for providing variable rigidity of the compression system; 7, device for implementing complex compression conditions; 8, computer-controlled measuring system for conducting and processing test results, including: 9, computer; 10, sixteen differential channel analogue-to-digital converter; 11, terminal board for connecting differential channels; 12, modules of the analogue direct-current strain-gauge signal amplifier for bridge circuits; 13, electronic force-measuring dynamometer; 14, extensometer for longitudinal deformation; and 15, extensometer for transverse deformation.

For performing measurements, an egg was placed horizontally on the lower immobile crosshead. The upper moving crosshead was set in motion and applied pressure at a constant speed that was adjustable in the range between 0.010 and 0.065 mm s^{-1}. Using special extensometers, the computer system recorded the complete compression diagram and the shell deformation in real time. Mathematical and statistical processing of the results was implemented using Microsoft Excel and STATISTICA 5.5 (StatSoft, Inc./TIBCO, Palo Alto, CA, USA).

3. Results

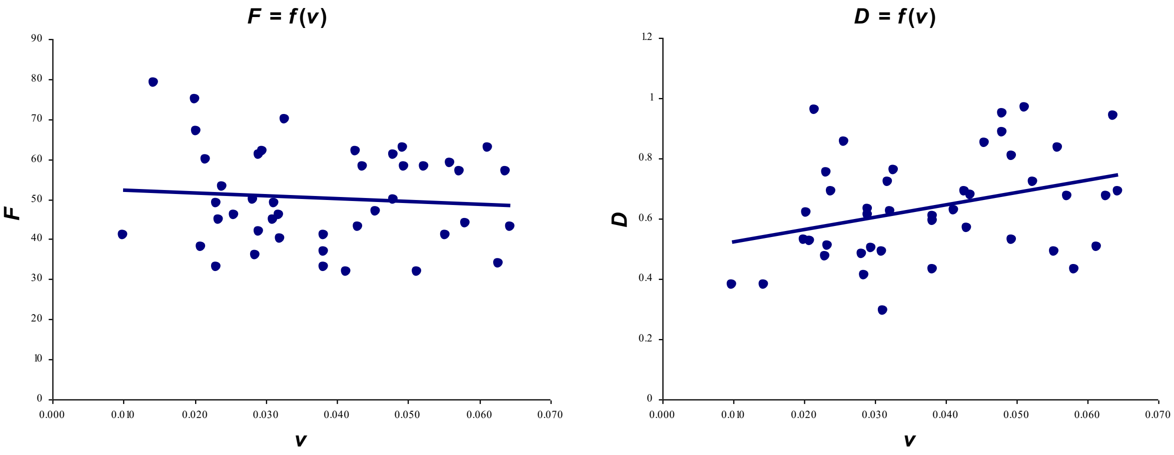
The summarised results from the 45 eggs in the form of indicators of shell strength (fracture force) and deformation, as well as the respective correlation coefficients are shown in Table 1.

Table 1

Data of measuring the egg variables, shell fracture force and deformation, and their intercorrelations with fracture force (R_F) and deformation (R_D).

Parameters	Max. value	Min. value	Mean	Standard deviation	R_F	R_D
Egg length, L (mm)	57.8	57.0	57.2	0.21	–0.209	0.034
Egg maximum breadth, B (mm)	40.0	38.9	39.3	0.26	–0.302	–0.246
Egg weight, W (g)	58.95	58.00	58.46	0.265	–0.328	–0.235
Shell fracture force, F (N)	79.00	32.00	50.23	12.077	1.000	0.065
Shell deformation, D (mm)	0.97	0.29	0.63	0.166	0.065	1.000
Shell compression speed, v (mm s^{-1})	0.064	0.010	0.038	0.015	–0.087	0.402

Graphical dependences of the two main parameters, i.e., the shell strength, F, and its deformation, D, on the load motion (compression) speed, v, are shown in Fig. 2.



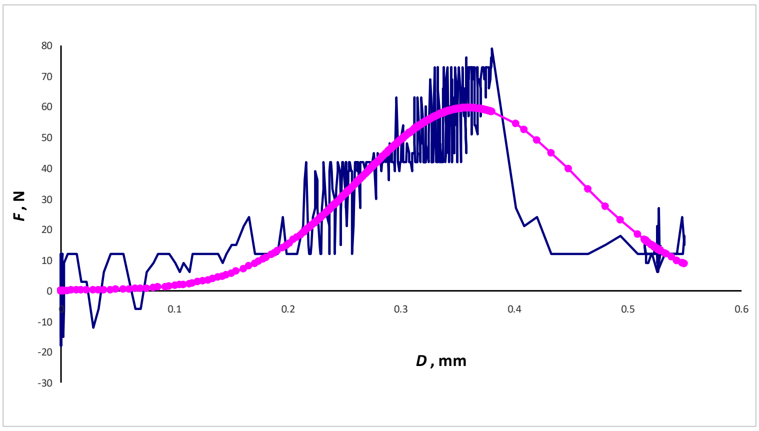
a b

Fig. 2. Dependences of the shell strength: (a) $F = -71.724v + 52.961$, $R^2 = 0.0076$, and (b) its deformation, $D = 4.543v + 0.4576$, $R^2 = 0.1612$, on the load motion (compression) speed, v.

In view of sensitivity of the ZD-100Pu device tension sensors, data on the shell deformation under the impact of an external load had the form of oscillograms approximated by a Gaussian curve, which most accurately described this process (Fig. 3). The function is considered in its initial form, i.e., as a composing product of the exponential function with a concave quadratic function (Pontes, 2018):

$$F = e^{aD^2 + bD + c} \tag{1}$$

where a, b and c are constant coefficients.



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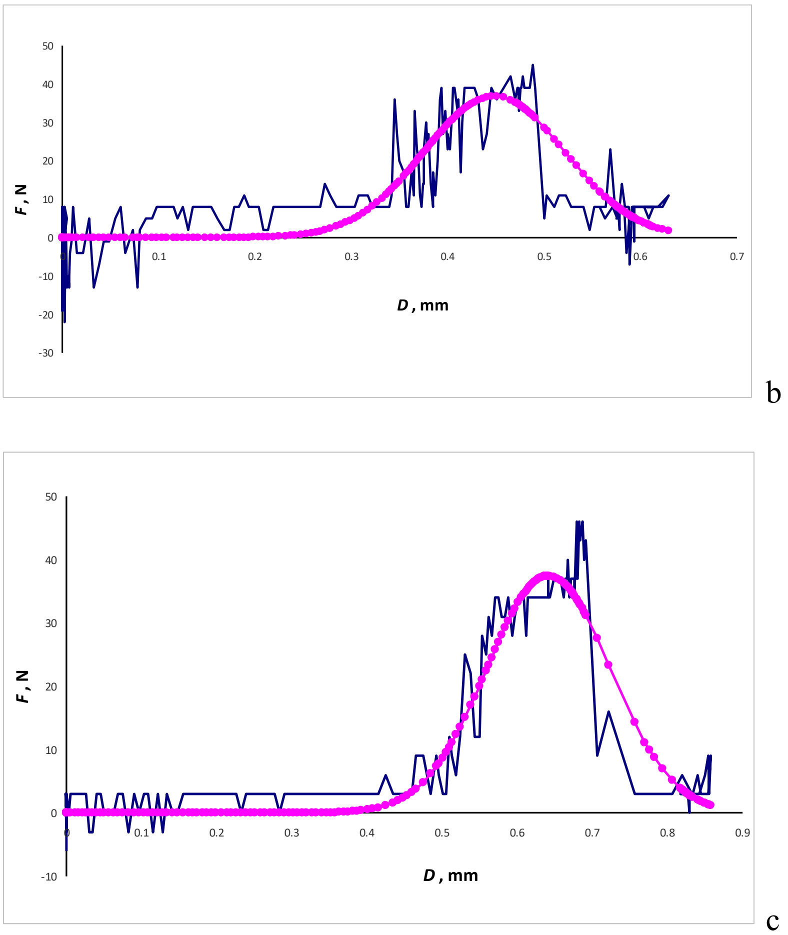

Fig. 3. Examples of the recorded oscillograms for the shell deformation, *D*, under the impact of an external load, *F*, at different load motion (compression) speeds, *v*: (a) 0.010 mm s^{-1}, (b) 0.031 mm s^{-1}, and (c) 0.064 mm s^{-1}.

The maximum values of the shell strength, $F_{\max}$, and deformation, $D_{\max}$, can be determined by equating to zero the derivative of Eq. (1):

$$\frac{dF}{dD} = e^{aD^2+bD+c} \cdot (2aD+b) = 0 \tag{2}$$

Since the exponent cannot be equal to zero, i.e., $e^{aD^2+bD+c} \neq 0$, the $D_{\max}$ value is determined from the expression $2aD+b=0$ as follows:

$$D_{\max} = -\frac{b}{2a} \tag{3}$$

Substituting Eq. (3) into Eq. (1), we obtain:

$$F_{\max} = e^{c-\frac{b^2}{4a}} \qquad (4)$$

Recalculating the values of $F_{\max}$ and $D_{\max}$ for each egg and comparing them with experimental data, we confirmed the adequacy of using the Gaussian curve as a theoretical function reflecting the dependence $F = f(D)$ as well as for predicting the egg strength by the value of the elastic shell deformation. The correlation coefficient, R, between the experimental and calculated data for $F_{\max}$ was 0.852 and that for $D_{\max}$ 0.990, with the respective graphical dependencies is shown in Fig. 4.

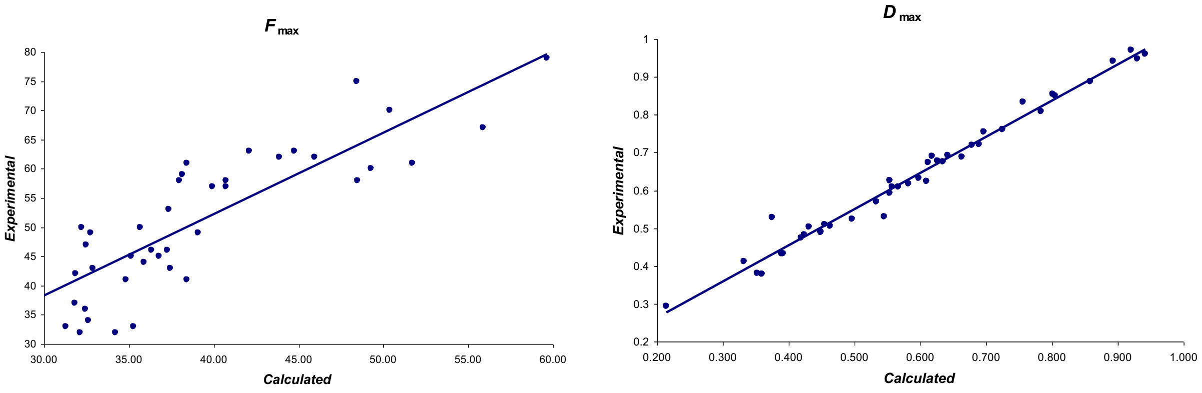

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Fig. 4. Graphical relationships between experimental and calculated data for $F_{\max}$ (a) and $D_{\max}$ (b).

It is assumed that the calculated $F_{\max}$ values obtained are more suitable than the experimental data because in the experiment $F_{\max}$ is taken as the maximum value of the respective oscillogram (Fig. 2). However, the average value between the peaks of its corresponding upsurge should obviously be accepted as a basis.

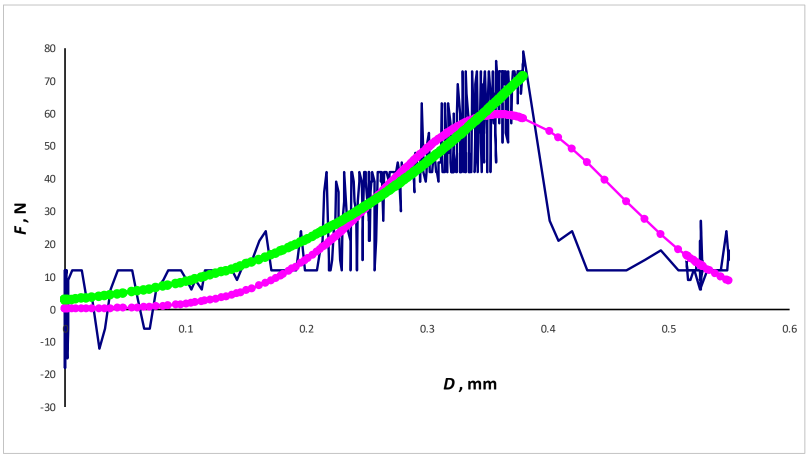
Thus, the problem of predicting the maximum compression that the shell can withstand was reduced to predicting the value of $F_{\max}$ from the indices of its non-destructive elastic deformation.

In determining the shell strength by the magnitude of non-destructive deformation, it is usually considered that the prediction will be the more accurate the greater the deflection can be achieved in the experiment (see the Introduction section). Considering this, analysis of the data was attempted within an interval limited by the minimum value of *F* obtained in the experiment, which according to Table 1 was 32 N. Thus, for further mathematical processing focus was on the interval from 0 to 30 N.

To develop a method for an optimal prediction of the shell strength, the following three hypotheses were tested.

3.1. Approximating shell deformation data by Gaussian function if non-destructive compression changes from 0 to 30 N

In this first hypothesis the appropriate data of *F* and *D* was approximated with the Gaussian function in the interval from 0 to 30 N for each of the studied eggs. As an example, the curves in Fig. 3 were overlaid with the calculated graphical dependencies (green lines) and are presented in Fig. 5.



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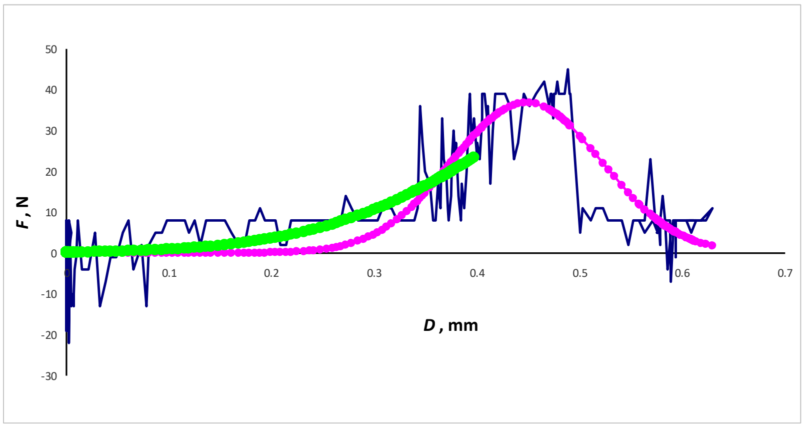

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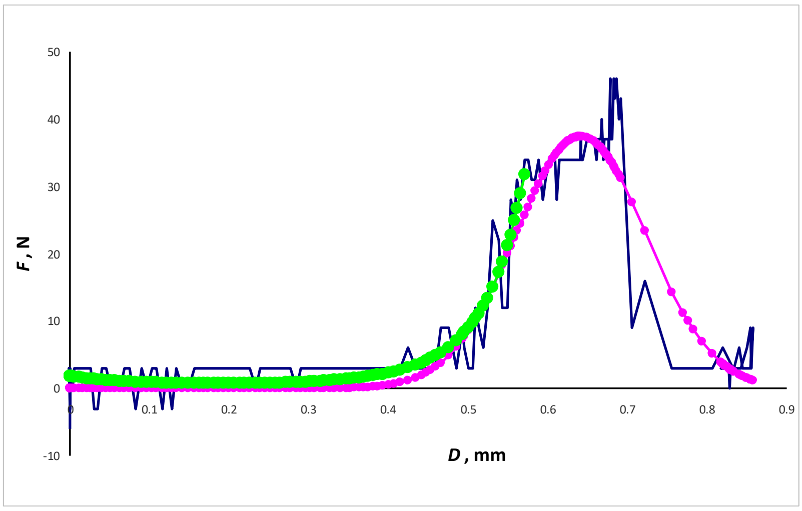

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Fig. 5. Examples of Gaussian function-assisted approximation (green line) of the shell deformation, *D*, if the area of non-destructive compression, *F*, changes from 0 to 30 N at the following *v* values: (a) 0.010 mm s^{-1}, (b) 0.031 mm s^{-1}, and (c) 0.064 mm s^{-1}.

Considering the approximated coefficients of the Gaussian functions, for each egg according to the respective Eqs. (3) and (4), the values of the maximum load and maximum deformation of the shell were recalculated. To differentiate the recalculated values from the previous calculated values, they were designated $F_{\max}(30N)$ and $D_{\max}(30N)$. Nevertheless, the correlation between the experimental and calculated data was found to be extremely low, i.e., it was clearly insufficient for the practical use. For the shell strength, it was 0.217, and for the maximum deformation, 0.316. This is shown graphically in Fig. 6.

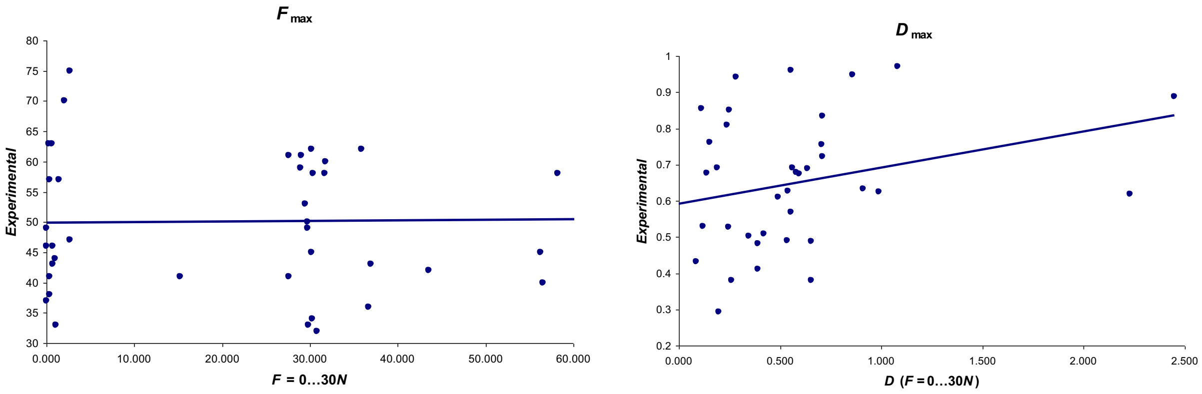

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Fig. 6. Graphical dependencies between experimental and calculation data $F_{\max}$ (a) and $D_{\max}$ (b) in the area of non-destructive compression from 0 to 30 N.

3.2. Calculating curve fitting function coefficients using three non-destructive measurements of the elastic shell deformation

Since it was not possible to identity of the equations reflecting the dependence $F = f(D)$ for the full range of destructive compressing loads and for the truncated range corresponding to its non-destructive portion from 0 to 30 N, our next hypothesis was to determine the coefficients *a*, *b*, and *c* from the curve fitting equation, Eq. (1), based on three key measurements of shell deformation resulted from the non-destructive load. The following three *F* values: 20, 25 and 30 N, and the respective measurements of deformation values, D_1, D_2 and D_3 were chosen. This was because at lower loads, the amount of deformation was not an indicative parameter as shown by the uniform plateau in Fig. 3.

To calculate the necessary coefficients of Eq. (1), the equation was rearranged:

$$D = \frac{\sqrt{b^2 - 4a(c - \ln F)} - b}{2a} \tag{5}$$

Details of how coefficient values for Eq. (5) are presented in Appendix A.

Thus, using the three shell deformation values, D_1, D_2 and D_3, and their corresponding values of F_1, F_2 and F_3, and using Eq. (5), the following set of equations was developed from which the coefficients *a*, *b* and *c* were determined by successive substitution:

$$\begin{cases} \ln F_1 = aD_1^2 + bD_1 + c \\ \ln F_2 = aD_2^2 + bD_2 + c \\ \ln F_3 = aD_3^2 + bD_3 + c \end{cases} \tag{6}$$

.

The value of the coefficient *a* was obtained from the first Eq. (6) as

$$a = \frac{\ln F_1 - bD_1 - c}{D_1^2} \tag{7}$$

Similarly:

$$c = \ln F_1 - b\frac{D_1 D_2}{D_1 + D_2} - \ln\frac{F_1}{F_2} \cdot \frac{D_1^2}{D_1^2 - D_2^2} \tag{8}$$

and:

$$b = \frac{\ln\frac{F_2}{F_3}D_1^2 - \ln\frac{F_1}{F_3}D_2^2 + \ln\frac{F_1}{F_2}D_3^2}{(D_1 - D_2)(D_1 - D_3)(D_2 - D_3)} \tag{9}$$

A detailed derivation of Eqs. (7) – (9) is presented in Appendix B.

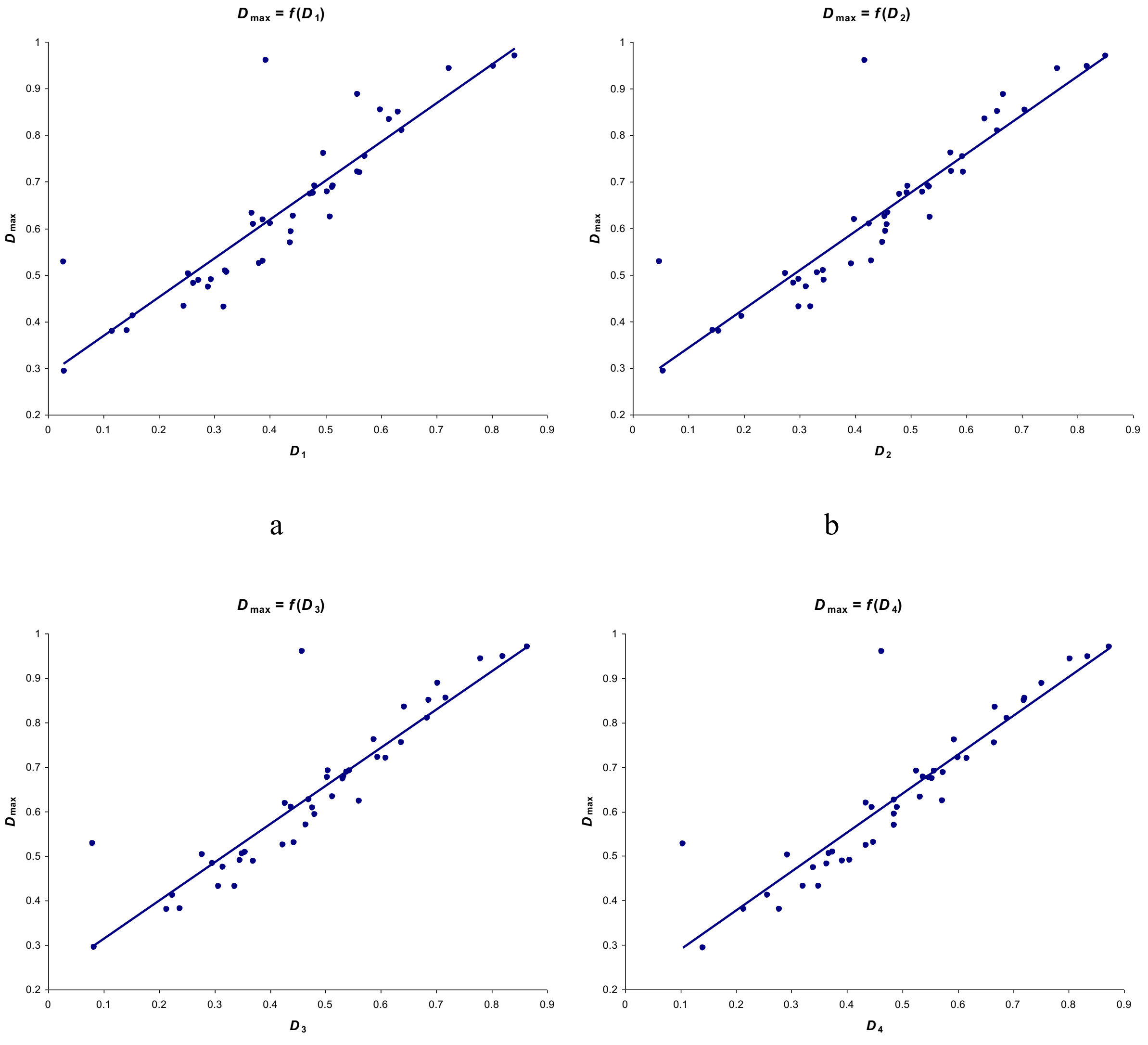
The values $F_1 = 20$ N, $F_2 = 25$ N and $F_3 = 30$ N and the respective values of D_1, D_2 and D_3 from the experimental data were used in Eqs. (7) – (9) and the values of coefficients *a*, *b*, and *c* were calculated from Eq. (1) using correlation analysis. Very low correlations were observed: for the coefficient *a*, –0.059; for *b*, 0.035; and for *c*, 0.115. Judging from these results, it was concluded that the second approach not applicable for predicting the values of $F_{\max}$ and $D_{\max}$.

Predictions also did not improve when using the average values of the coefficients *a*, *b*, and *c* in Eq. (4), since their variability was high amounting ±52% for *a*, ±65% for *b*, and ±103% for *c*. Thus, a third approach was therefore explored for predicting shell strength.

3.3. Predicting the shell strength $F_{\max}$ using non-destructive elastic deformation measurement values in relation to compression speed

The next hypothesis tested was to evaluate the prediction of the shell strength characteristics by increasing the number of measured values of its elastic deformation in the area of non-destructive egg compression. For this, along with the previously assessed three values of 20, 25 and 30 N, two more values, i.e., 10 and 15 N were added. Thus, for our further calculations for the third approach, the readings of elastic deformation D_1 to D_5 at non-destructive compressions 10, 15, 20, 25 and 30 N respectively ($F_1 - F_5$) were used.

To estimate the significance of the chosen values of D_1 to D_5, the appropriate graphical dependencies of $D_1 - D_5$ were compared with the corresponding values relative to $D_{\max}$ (Fig. 7).



a

b

c d

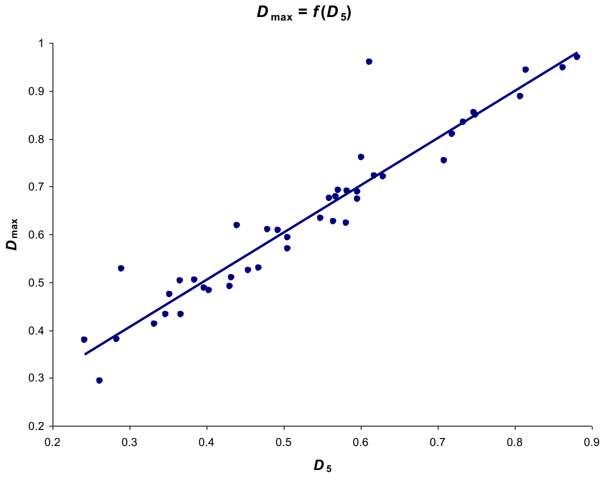


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Fig. 7. Plots of relationships between the maximum shell deformation D_{max} and, accordingly, its deformation: (a) D_1 at compression of 10 N, $D_{max} = 0.833D_1 + 0.2865$, $R^2 = 0.7885$; (b) D_2 at 15 N, $D_{max} = 0.8321D_1 + 0.2606$, $R^2 = 0.8085$; (c) D_3 at 20 N, $D_{max} = 0.8604D_1 + 0.2277$, $R^2 = 0.8178$; (d) D_4 at 25 N, $D_{max} = 0.8745D_1 + 0.2029$, $R^2 = 0.8112$; and (e) D_5 at 30 N, $D_{max} = 0.9866D_1 + 0.1114$, $R^2 = 0.9058$.

Each of the obtained linear functions was approximated by the respective equations (shown in the graphs of Fig. 7). The obtained correlation coefficients were very high, confirming the validity of using the selected key points of shell compression. At the same time, the use of intermediate values of elastic deformation improved the predictive accuracy of D_{max} with a corresponding increase in the accuracy of the non-destructive compression values.

Since all the obtained dependences (Fig. 7) had a linear characteristic, to approximate the dependences of the calculated maximum compression value on the values of $D_1 - D_5$, a full multifactorial linear equation was used:

$$F_{max} = k_0 + k_1D_1 + k_2D_2 + k_3D_3 + k_4D_4 + k_5D_5 + k_6D_1D_2 + k_7D_1D_3 + k_8D_1D_4 + k_9D_1D_5 + k_{10}D_2D_3 +$$

$$+ k_{11}D_2D_4 + k_{12}D_2D_5 + k_{13}D_3D_4 + k_{14}D_3D_5 + k_{15}D_4D_5 + k_{16}D_1D_2D_3 + k_{17}D_1D_2D_4 + k_{18}D_1D_2D_5 +$$

$$+ k_{19}D_2D_3D_4 + k_{20}D_2D_3D_5 + k_{21}D_3D_4D_5 + k_{22}D_1D_2D_3D_4 + k_{23}D_1D_2D_3D_5 + k_{24}D_2D_3D_4D_5 +$$

$$+k_{25}D_1D_2D_3D_4D_5 \tag{10}$$

where k_0 to k_{25} are constant coefficients obtained as a result of approximation.

The values of the coefficients k_0 to k_{25} are presented in Table 2 (column 'All range').

Table 2

Calculation data for constant coefficients in Eq. (10).

Coefficient	Values of constant coefficients depending on compression speed, v (mm s^{-1})			
	All range	0.010–0.030	0.031–0.050	0.051–0.064
k_0	1556.24	–283.06	721.98	1099.59
k_1	6539.20	23802.81	–6788.27	–234.63
k_2	–11624.95	–4484.89	–3798.82	–247.61
k_3	–5856.29	21755.73	3686.18	–1342.04
k_4	663.51	–18377.19	3084.40	–1027.10
k_5	–4842.07	–8394.21	–1642.17	–2123.49
k_6	–21626.46	–25663.11	3903.03	–610.22
k_7	–34676.35	8614.15	–14353.88	1190.39
k_8	57217.78	–11171.57	20240.28	2332.43
k_9	–31914.40	–67079.60	16518.22	1590.64
k_{10}	55262.47	10526.55	–17359.17	–1031.51
k_{11}	–26822.80	–17243.40	4264.10	208.06
k_{12}	54220.71	15902.56	11494.34	–474.98
k_{13}	–3829.02	–44062.63	13949.20	1299.15
k_{14}	23509.63	–29296.66	2616.16	560.92
k_{15}	–11920.28	94062.31	–29355.02	1216.75
k_{16}	36796.63	59565.52	–3527.05	–137.49
k_{17}	–32687.73	40067.46	–17351.31	387.88

k_{18}	18916.70	1187.39	935.21	–160.94
k_{19}	–32183.58	–16463.68	10917.89	–196.61
k_{20}	–112262.71	–1185.80	20932.47	–737.56
k_{21}	4540.73	8297.49	–14349.62	1184.85
k_{22}	14437.86	16134.78	–16912.35	–179.87
k_{23}	30740.49	12996.69	–4763.70	–601.25
k_{24}	70025.73	–36848.27	5102.90	–1182.37
k_{25}	–44791.44	–35481.14	11442.11	–1232.53

However, the use of Eq. (10) showed a significantly lower correlation, at $R^2 = 0.568$, and therefore did not correspond to the required accuracy.

To solve this problem, a further modification in data processing was investigated where the curve fitting options were divided into three parts, depending on the shell compression speed. The data was split into the following intervals: (i) 0.010 to 0.030 mm s^{-1}, (ii) 0.031 to 0.05 mm s^{-1}, and (iii) 0.051 to 0.065 mm s^{-1}. The approximation for each interval was performed using Eq. (10), and the results are given in the respective columns of Table 2.

Assessment of the obtained results confirmed their adequacy. For all three speed intervals, the correlation coefficient was the highest possible, at $R^2 = 0.99999$.

Our attempts to simplify Eq. (10) did not lead to any improvement.

4. Discussion

Being nature's technical ceramic (Hahn et al., 2017), eggshell is a naturally engineered packaging of the egg. We have reported here on experiments for estimating eggshell strength that involved eggs significantly aligned by their morphological parameters (Table 1). For example, the egg mass fluctuated within less than 1%, and the geometrical dimensions even less. Such uniformity of products, due to the intensive breeding work, is a bonus for the egg poultry industry.

However, at the same time, working with such objects has disadvantages for researchers. Despite the apparent similarity of eggs, the strength characteristics of their shells are quite different from one another. For example, fluctuations in the force required to break an egg can be more than ±50% of their mean. A similar scatter of values has been observed in shell deformation measurements. This diversity, according to the results of fundamental research by Solomon (2010), Bain (1992, 2005) and others, is associated with the structural features of the shell that at present cannot be assessed using non-destructive methods. Thus, in this study, we were unable to rely on the geometric egg parameters for predictions of strength which in our previous experiments were incorporated, either separately (Narushin, 2001; Narushin et al., 2004), or in combination with data on the non-destructive deformation of the shell (Narushin, 1998). In this regard, the only parameter used for shell strength prediction was shell deformation measured using non-destructive compression.

In this work, when the shell compression speed range was rather small, i.e., 0.010 to 0.065 m s^{-1}, there was not a sufficiently close relationship between compression speed and shell strength (Fig. 2a). The obtained linear trend can be considered somewhat arbitrary. Nevertheless, the data confirms the results of Altuntaş and Şekeroğlu (2008) suggesting that at low shell compression speeds, a slightly greater force is required to destroy the egg, although the correlation coefficient obtained was too small to make an unambiguous conclusion. Perhaps, the assumptions of Carter (1977) about a different nature of the influence of the compression speeds on shell strength were correct. However, for our studies, the speed of load impact on the shell was an important and even fundamental factor for the non-destructive prediction of shell strength. It can be unequivocally stated that this indicator should be controllable and be the same for all eggs involved in the measurements. A minimum requirement for tests is that speed values should be within a small range. When examining taking the number of eggs in each compression speed group the largest number (17 eggs) corresponded to the group at v = 0.031 – 0.050 mm s^{-1}. Thus, when selecting shell compression speed is advisable to choose from this range of speeds.

Low shell compression speeds and a right choice of instrument for detecting functional dependences of compression on the magnitude of elastic deformation, leading to curvilinear dependences that were accurately approximated by Gaussian curves. This gave us the ability to mathematically calculate the critical compression peak at which the shell breaks. Low compression speed also contributed to the fact that the egg could withstand sufficiently high non-destructive loads up to 30 N and more. Using the readings of the shell deformation for a given load, it is possible to accurately predict the magnitude of the maximum elastic deformation. It should be recalled that even in the well-researched area of metallurgy there is no precedent for predicting the strength of a body from its elastic deformation. Rewriting the best-fit equation into its more general the following relationship was obtained:

$$D_{\max} = 0.9866 D_{30} + 0.1114 \tag{11}$$

where D_{30} is non-destructive shell deformation that was maximum permissible in the framework of our experiments and equal to a load of 30 N.

Although two of our calculation approaches failed (sections 3.1 and 3.2), we believe that our hypothesis can work on a different chicken egg sample, or on the eggs of other similar bird species (e.g., quail), for which much lower loads are required. In this case, the provided calculations may be useful for predicting the shell strength of those eggs.

One cannot exclude that, for eggs from other chicken crosses or those obtained under different conditions of chicken maintenance and/or feeding, the chosen maximum non-destructive load of 30 N can lead to damage to the shell. Since the purpose of this work was only to develop a methodology for such research, the choice of the 30 N level was adequate only for the used sample of eggs. We could suggest that in a practical use of this method, it would be necessary to carry out a number of destructive experiments, as a result of which the limiting value of the maximum permissible non-destructive load could be identified that would guarantee the integrity of the eggs under study.

5. Conclusions

1. In this study, the non-destructive analysis of egg strength characteristics was carried out using an experimental measurement instrument that produced values of the elastic shell deformation, *D*, at a constant non-destructive load on the shell. A curvilinear dependence of the egg fracture force, *F*, on the deflection value was derived and found suitable for very low shell compression speeds (0.03 to 0.05 mm s^{-1}).
2. It is suggested that when using the principle of curvilinearity, the resulting dependence can be approximated by a suitable equation, from which the formula for determining the value of the shell strength can be derived by using analytical mathematical expressions.
3. For an accurate prediction of the maximum value of the elastic shell deformation, it is important to use its intermediate values corresponding to those closest to the maximum permissible ones, which do not cause destruction (damage) of the egg. In our experiment, the ultimate non-destructive load was 30 N.
4. To predict the eggshell strength, i.e., the maximum load at which the shell breaks down, it is advisable to use measurements of its non-destructive elastic deformation at not less than five points are used to obtain the curvilinear dependence.
5. It is emphasised that our research has demonstrated methodological prerequisites for achieving accurate calculations of the shell strength characteristics in eggs aligned according to their morphological parameters. In this regard, the obtained experimental dependences seem adequate only for the sample of eggs used in the study. Nevertheless, the proposed approach could be used to develop an appropriate shell strength calculation technique depending on the available instrument for assessing the elastic shell deformation in order to control the specific shell strength properties of the studied eggs.

Declaration of competing interest

The authors have no conflict of interest to declare.

Appendices A and B. Supplementary data

Supplementary data to this article can be found online at

References

Altuntaş, E., & Şekeroğlu, A. (2008). Effect of egg shape index on mechanical properties of chicken eggs. *Journal of Food Engineering*, *85*, 606–612. https://doi.org/10.1016/j.jfoodeng.2007.08.022

Bain, M. M. (1992). Eggshell strength: A relationship between the mechanism of failure and the ultrastructural organization of the mammillary layer. *British Poultry Science*, *33*, 303–319. https://doi.org/10.1080/00071669208417469

Bain, M. M. (2005). Recent advances in the assessment of eggshell quality and their future application. *World's Poultry Science Journal*, *61*, 268–277. https://doi.org/10.1079/WPS200459

Carter, T. C. (1970). The hen's egg: some factors affecting deformation in statically loaded shells. *British Poultry Science*, *11*, 15–38. https://doi.org/10.1080/00071667008415789

Carter, T. C. (1977). The hen's egg: Relationship of mean strain energy at shell fracture to shell compression speed, the nature of the compressing body and the location on the shell of the point of contact. *British Poultry Science*, *18*, 205–211. https://doi.org/10.1080/00071667708416352

Carter, T. C. (1978). The hen's egg: Fracture of shells loaded very slowly. *British Poultry Science*, *19*, 669–679. https://doi.org/10.1080/00071667808416526

Chausov, M., Maruschak, P., & Pylypenko, A. (2020). Influence of changes in structural and mechanical condition of aluminium alloys caused by impact-oscillatory loading on their fatigue life. In I. Kabashkin, I. Yatskiv, & O. Prentkovskis (Eds.), *Reliability and statistics in transportation and communication, RelStat 2019, Lecture Notes in Networks and Systems*

(Vol. 117, pp. 491–499). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-030-44610-9_48

Chausov, M., Pylypenko, A., Maruschak, P., Tkachuk, S., & Menou, A. (2018). Express method to estimate structural imperfection and bone tissue status. *Journal of Mechanical Engineering* [*Strojnícky Časopis*], *68*, 271–280. https://doi.org/10.2478/scjme-2018-0040

Chausov, N. G., Voityuk, D. G., Pilipenko, A. P., & Kuz'menko, A. M. (2004). Setup for testing materials with plotting complete stress–strain diagrams. *Strength of Materials*, *36*, 532–537. https://doi.org/10.1023/B:STOM.0000048404.91503.89

Hahn, E. N., Sherman, V. R., Pissarenko, A., Rohrbach, S. D., Fernandes, D. J., & Meyers, M. A. (2017). Nature's technical ceramic: the avian eggshell. *Journal of the Royal Society Interface*, *14*, 20160804. https://doi.org/10.1098/rsif.2016.0804

Juang, J. Y., Chen, P. Y., Yang, D. C., Wu, S.-P., Yen, A., & Hsieh, H.-I. (2017). The avian egg exhibits general allometric invariances in mechanical design. *Scientific Reports*, *7*, 14205. https://doi.org/10.1038/s41598-017-14552-0

Macleod, N., Bain, M. M., & Hancock, J. W. (2006). The mechanics and mechanisms of failure of hens' eggs. *International Journal of Fracture*, *142*, 29–41. https://doi.org/10.1007/s10704-006-9018-5

Marushchak, P., Hlad'o, V., Bishchak, R., & Pylypenko, A. (2010). Influence of thermocyclic operation on the degradation of properties of a heat-resistant steel. *Materials Science*, *46*, 102–107. https://doi.org/10.1007/s11003-010-9269-1

Narushin, V. G. (1998). Shell strength as an indicator of egg quality: methods for estimation. In *Proceedings of the 10th European Poultry Conference* (Vol. 2, pp. 684–687). Jerusalem, Israel.

Narushin, V. G. (2001). What egg parameters predict best its shell strength? In *Proceeding of the IX European Symposium on the Quality of Eggs and Egg Products* (pp. 349–355). Kusadasi, Turkey.

Narushin, V. G., & Chausovsky, G. A. (199)7. Improved method and techniques for measuring the elastic deformation in thinwalled casings. In *Proceedings of the International Conference 'Experimental Model Research and Testing of Thin-walled Structures'* (pp. 79–82). Prague, Czech Republic.

Narushin, V. G., & Morgun, A. Y. (1995). Shell deformation in research of egg strength. In *Proceeding of the 11th International Symposium on Current Problems in Avian Genetics* (pp. 164–166). Balice near Krakow, Poland.

Narushin, V. G., & Romanov, M. N. (1994). Modelling growth of chick embryo. In *Proceedings of the 9th European Poultry Conference: Plenary Papers and Contributed Papers* (Vol. 1, pp. 411–412). Glasgow, Scotland, UK.

Narushin, V. G., & Romanov, M. N. (2000). [Some ecological peculiarities of chicken egg incubation]. *Visnyk Sums'kogo derzhavnogo agrarnogo universytetu, Series "Veterinary Medicine"*; Sumy, Ukraine: Sumy State Agrarian University, Issue 5, 92–93.

Narushin, V. G., & Romanov, M. N. (2001). [Influence of egg parameters on hatchability (a research review)]. *Ptakhivnytstvo* [*Poultry Farming*], Issue 51, 422–429.

Narushin, V. G., & Romanov, M. N. (2002a). Physical characteristics of chicken eggs in relation to their hatchability and chick weight. In *CD-ROM Proceedings of 2002 ASAE Annual International Meeting/CIGR World Congress* (paper #026066). Chicago, IL, USA. https://doi.org/10.13031/2013.9226

Narushin, V. G., & Romanov, M. N. (2002b). Relationship between physical characteristics and results of hatching in chicken eggs. *Archiv für Geflugelkunde*, *66* (Sonderheft II), 128.

Narushin, V. G., & Romanov, M. N. (2002c). Egg physical characteristics and hatchability. *World's Poultry Science Journal*, 58, 297–303. https://doi.org/10.1079/WPS20020023

Narushin, V. G., Romanov, M. N., & Bondarenko, Yu. V. (1994). Studies on chick embryo sex determination and manipulation in the countries of the former USSR — a review. 1. Sex differences in eggs. In *Proceedings of the 9th European Poultry Conference: Plenary Papers and Contributed Papers* (Vol. 1, pp. 320–321). Glasgow, Scotland, UK.

Narushin, V. G., Romanov, M. N., & Bogatyr, V. P. (1996). [On relationship between chicken egg morphological parameters and chick sex]. In *Abstracts of the 2nd Ukrainian Poultry Conference* (pp. 92–93). Borky, Ukraine.

Narushin, V. G., Romanov, M. N., & Sakhatsky, N. I. (1997). Modelling growth of chick embryo: correction for egg weight. *Animal Production Review, Applied Science Reports*, *31*, 55–57.

Narushin, V. G., Romanov, M. N., & Bogatyr, V. P. (1998). Method for preincubational prediction of embryo sex in chicken eggs. In *Proceedings of the 8th World Conference on Animal Production: Contributed Papers* (Vol. 1, pp. 832–833). Seoul, Korea.

Narushin, V. G., Romanov, M. N., & Bogatyr, V. P. (2002). AP–Animal Production Technology: Relationship between pre-incubation egg parameters and chick weight after hatching in layer breeds. *Biosystems Engineering*, *83*, 373–381. https://doi.org/10.1006/bioe.2002.0122

Narushin, V. G., van Kempen, T. A., Wineland, M. J., & Christensen, V. L. (2004). Comparing infrared spectroscopy and egg size measurements for predicting eggshell quality. *Biosystems Engineering*, *87*, 101–107. https://doi.org/10.1016/j.biosystemseng.2003.12.006

Narushin, V. G., Romanov, M. N., & Griffin, D. K. (2021). Non-destructive evaluation of the volumes of egg shell and interior: theoretical approach. *Journal of Food Engineering*, *300*, 110536. https://doi.org/10.1016/j.jfoodeng.2021.110536

Nedomová, Š., Trnka, J., Dvořáková, P., Buchar, J., & Severa, L. (2009). Hen’s eggshell strength under impact loading. *Journal of Food Engineering*, *94*, 350–357. https://doi.org/10.1016/j.jfoodeng.2009.03.028

Nedomová, Š., Buchar, J., & Strnková, J. (2014). Goose's eggshell strength at compressive loading. *Potravinárstvo – Slovak Journal of Food Sciences*, *8*, 54–61. https://doi.org/10.5219/346

Nedomová, Š., Kumbár, V., Trnka, J., & Buchar, J. (2016). Effect of the loading rate on compressive properties of goose eggs. *Journal of Biological Physics*, *42*, 223–233. https://doi.org/10.1007/s10867-015-9403-2

Pontes, E. A. S. (2018). A brief historical overview of the Gaussian curve: from Abraham De Moivre to Johann Carl Friedrich Gauss. *International Journal of Engineering Science*, *7*(6), 28–34.

Romanov, M. N. (1995). Qualitative and quantitative egg characteristics in laying hens of different genotype. In *Egg and Egg Products Quality, Proceedings of the 6th European Symposium on Quality of Eggs and Eggs Products* (pp. 203–206). Zaragoza, Spain.

Romanov, M. N., Narushin, V. G., & Sakhatsky, N. I. (1994). Studies on chick embryo sex determination and manipulation in the countries of the former USSR — a review. 2. Shifting of sex ratio. In *Proceedings of the 9th European Poultry Conference: Plenary Papers and Contributed Papers* (Vol. 1, pp. 324–326). Glasgow, Scotland.

Schoorl, P., & Boersma, H. Y. (1962). Research on the quality of the egg shell. In *Proceedings of the 12th World's Poultry Congress* (pp. 432–435). Sydney, Australia.

Shomina, N. V., Tkachenko, S. M., Tagirov, M. T., & Tereshchenko, O. V. (2009a). [Monitoring the quality of hatching eggs during storage]. *Efektyvne ptakhivnytstvo* [*Effective Poultry Farming*], Issue 11, 29–33.

Shomina, N. V., Tkachenko, S. M., Tagirov, M. T., & Tereshchenko, O. V. (2009b). [Dependence of egg hatchability on the level of blastodermal cell death before setting eggs for incubation]. *Ptakhivnytstvo* [*Poultry Farming*], Issue 63, 236–243.

Solomon, S. E. (2010). The eggshell: strength, structure and function. *British Poultry Science*, *51*, 52–59. https://doi.org/10.1080/00071668.2010.497296

Tagirov, M. T., Shomina, N. V., Artemenko, A. B., Tkachenko, S. N., Baydevlyatova, O. N., Tereshchenko, A. B., & Sakhatsky, N. I. (2009a). [*Incubation of poultry eggs: guidelines*]. Kharkiv, Ukraine: PRI NAAS.

Tagirov, M. T., Ogurtsova, N. S., & Tereshchenko, A. V. (2009b). [Analysis of hatchability problems for incubated eggs]. *Ptakhivnytstvo* [*Poultry Farming*], Issue 63, 199–215.

Trnka, J., Nedomová, Š., Kumbár, V., Šustr, M., & Buchar, J. (2016). A new approach to analyze the dynamic strength of eggs. *Journal of Biological Physics*, *42*, 525–537. https://doi.org/10.1007/s10867-016-9420-9

Voisey, P. W. (1975). Field comparison of two instruments for measuring shell deformation to estimate eggshell strength. *Poultry Science*, *54*, 190–194. https://doi.org/10.3382/ps.0540190

Voisey, P. W., & Hamilton, R. M. G. (1976). Factors affecting the non-destructive and destructive methods of measuring egg shell strength by the quasi-static compression test. *British Poultry Science*, *17*, 103–124. https://doi.org/10.1080/00071667608416254

Voisey, P. W., & Hunt, J. R. (1967). Relationship between applied force, deformation of eggshells and fracture force. *Journal of Agricultural Engineering Research*, *12*, 1–4. https://doi.org/10.1016/S0021-8634(67)80029-5

Voisey, P. W., & Hunt, J. R. (1969). Effect of compression speed on the behaviour of eggshells. *Journal of Agricultural Engineering Research*, *14*, 40–46. https://doi.org/10.1016/0021-8634(69)90065-1

Voisey, P. W., & Hunt, J. R. (1976). Comparison of several eggshell characteristics with impact resistance. *Canadian Journal of Animal Science*, *56*, 299–304. https://doi.org/10.4141/cjas76-035

Voisey, P. W., & MacDonald D. C. (1978). Laboratory measurements of eggshell strength. 1. An instrument for measuring shell strength by quasi-static compression, puncture and non-destructive deformation. *Poultry Science*, *57*, 860–869. https://doi.org/10.3382/ps.0570860

Voisey, P. W., & Robertson, G. D. (1969). The rapid measurement of eggshell strength. *Journal of the Canadian Society of Agricultural Engineering*, *11*, 6–8, 11.

Voisey, P. W., Hamilton, R. M. G., & Thompson, B. K. (1979). Laboratory measurements of eggshell strength: 2. The quasi-static compression, puncture, non-destructive deformation, and specific gravity methods applied to the same egg. *Poultry Science*, *58*, 288–294. https://doi.org/10.3382/ps.0580288